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Research Paper

Waste 2 worth: Advancing the circular economy with automation

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Abstract: Conventional waste management methods are very harmful for human health and environment. Many materials such as metals, plastics and paper can be recycled but in conventional waste management systems they are sent to landfills. Landfills occupy large amounts of land that could be used for other purposes. As landfills expand they impact ecosystems by emitting green house gases, different types of pollution, high carbon foot prints spreading so many hazardous diseases of animals and human and reducing biodiversity. Automated waste management system are playing a pivotal role towards a circular economy where the aim shifts from traditional method of take, make, dispose model to the systems that emphasize sustainable future and minimal waste generation. This paper explores the unification of automation technologies in waste management processes like, the Internet of Things (IoT), Robotics, Cloud Computing, Artificial Intelligence (AI) and Machine Learning are enhancing waste collection, sorting, recycling and disposal processes, Automation enhances the efficiency speed, reduces labour cost and human errors in waste sorting and collection leading to higher accuracy in recycling processes. This paper also highlights benefits, minimizing waste and reducing environmental impact and support for the circular economy.

Keywords: Automation, Artificial Intelligence, Internet of Things.

Introduction:

India generates around 1.45 lakh metric tonnes of non-liquid waste every day, 85% of which is dry waste. It has various constituents like ceramic, paper, tyres, cardboard, metals, textiles, plastic etc. Waste management plays a crucial role in circular economy and this is possible by application of Automated waste management means integration of innovative technologies like Machine Learning, Artificial Intelligence (AI), Robotics and IoT (Internet of Things to minimize the processes of waste collection, sorting, recycling and disposal

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(Fang *et. al.*, 2023). This not only makes waste management more efficient but also plays a significant role in support of circular economy. The circular economy relies on the continuous circulation of resources by following the 7R's concept - Recycle, Rethink, Reduce, Reuse, Repair, Refurbish and Recover **(**Borah and Kumar, 2024). A circular economy is a restorative framework which focuses on reducing waste and using resources to the maximum. Instead of the conventional take-make-dispose model, circular economy promotes reusing, recycling and repairing commodities to maximize the usage duration of materials. The shift towards circular economy is gaining momentum as environmental concerns rise and industries are looking for sustainable solutions. Automated waste management systems are the key to this transformation. By automating waste collection, sorting and recycling processes, proficiency & precision of waste processing improves in higher percentage of materials being recycled, less contamination and waste minimization. These systems can also recover valuable materials like metals, plastics and paper which would otherwise be lost.

Major Applications of AI

AI is revolutionizing waste management to become more productive, cost-saving and environment friendly. There are some AI powered approaches listed below .

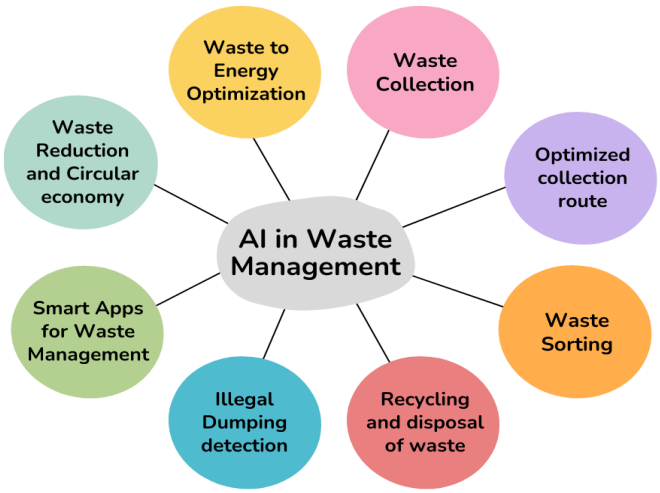

Figure: 1. Role of AI in Waste Management

Waste Collection & Route Optimization

Traditional garbage cans only collect garba ge and sanitation workers need to manually inspect them to determine the level of trash in the cans. This method is not effective for regular waste disposal checks. In addition the frequent filling of containers creates conditions that promote the growth of disease causing organisms and insects (Noiki *et. al.*, 2021). Hence coming up with intelligent garbage bin or Smart bins or AI powered bins for the waste collection and monitoring systems to handle garbage. Smart bins are equipped with IoT and AI sensors that can sense the level of fill in the bin and inform waste management crews when they must be emptied.

This avoids bins overflowing and lessens u nnecessary trips. Cameras and other sensors can also identify the type of waste being put into the bin.

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This data is usually sent wirelessly via Wi Fi or Bluetooth so that waste management teams can better plan collection routes and avoid unnecessary pickups. This optimizes collection routes and avoids overflow and save the environment (Zoumpoulis *et. al.*, 2024).

Optimized waste collection routes, employing tools such as route optimization software and algorithms aim to reduce travel time, distance and fuel usage while maximizing the number of pickups per trip, thereby enhancing efficiency and lowering costs.

Waste – Sorting & Recycling

Traditional sorting is time consuming and error-prone, whereas AI-based systems mechanize and maximize the process (Raman *et. al.*, 2023), Increased recycling rates, lowers contamination and increases material recovery. Minimizes labor expenses and e nhances operational effectiveness so cost effective. AI enhances sustainability through maximum material recovery as fewer waste in Landfills. Machine learning, Computer vision, Robotic sorting are some important features of AI based sorting and recycling.

Robotic Waste Sorters

AI-operated robotic arms rapidly pick and sort refuse based on material category. AI-based robotic sorters can segregate and categorize wasteful materials efficiently making the sorting operation faster and recycling efficiency more improved (Koskinopoulou *et. al.*, 2021)).

Machine Learning Algorithms

Machine Learning (ML) has a big impact on waste management. It makes things more productive, cuts costs, and helps the environment (Yan *et. al.*, 2025). For instance, cameras and sensors take pictures of trash, and ML systems sort items into recyclable or non-recyclable groups with great precision. ML-driven robots do sorting jobs better than people which means less contamination in recyclables and higher recycling rates overall. Machine learning algorithms can achieve high accuracy in identifying and sorting waste leading to better recycling rates.

Computer Vision & Image Recognition

Real-time waste analysis by AI-enabled cameras to detect materials (plastic, glass, metal, paper) etc. AI analyses images of waste materials using deep learning models to classify waste accurately. This helps in better segregation of recyclables and non-recyclables improving recycling efficiency.

Illegal Dumping Detection

Illegal dumping is a serious public health and environmental concern (Pathak *et. al.*, 2024). AI-based CCTV cameras scan video footage to identify suspicious dumping. AI identifies waste streams and dumping locations through image recogniti on.

AI employs GIS (Geographic Information Systems) to identify hotspots of illegal dumping. AI assists cities in maximizing patrols and waste management plans.

AI-powered systems can also help recover precious materials like silver,gold and rare earth elements from e- waste and identify reusable parts like circuit boards, batteries, and screens from electronic waste (e-waste). AI facilitates the adoption of sophisticated chemical recycling strategies for disintegration complex plastics into reusable raw materials. AI assists in determining the best chemical reactions to increase recycling yields.AI assists authorities in more effectively planning the proper execution of waste collection, disposal, and recycling by forecasting

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waste generation patterns based on data from cities, industries, and households.

Waste to Energy Optimization using AI

By increasing energy recovery, decreasing emissions and improving efficiency, artificial intelligence (AI) is significantly contributing to the optimisation of waste-to-energy (WTE) processes (Melinda et al., 2024). AI is being applied to WTE optimisation by following ways like AI examines the chemical & physical characteristics of waste using sensor technology and machine learning models. It forecasts the energy capacity of various waste materials including paper, plastic, and organic waste aids in choosing the ideal waste mixture for gasification or combustion, guaranteeing the highest possible energy output. Intelligent Sorting for maximum efficiency Robotic Sorting systems driven by fuel AI separate non-combustible waste (like glass and metals) from materials with a high energy content (like plastics and biomass) enhances the quality of RDF (refuse-derived fuel) used in WTE facilities. AI detects early signs of equipment failure in turbines, boilers, and filters reduces maintenance costs and prevents unexpected plant shutdowns improves overall operational efficiency by ensuring continuous power generation (Sharanya et al., 2021). AI predicts energy consumption and optimizes the distribution of power generated from waste. Uses smart grid technology to balance WTE-generated power with sustainable energy sources like wind & solar.

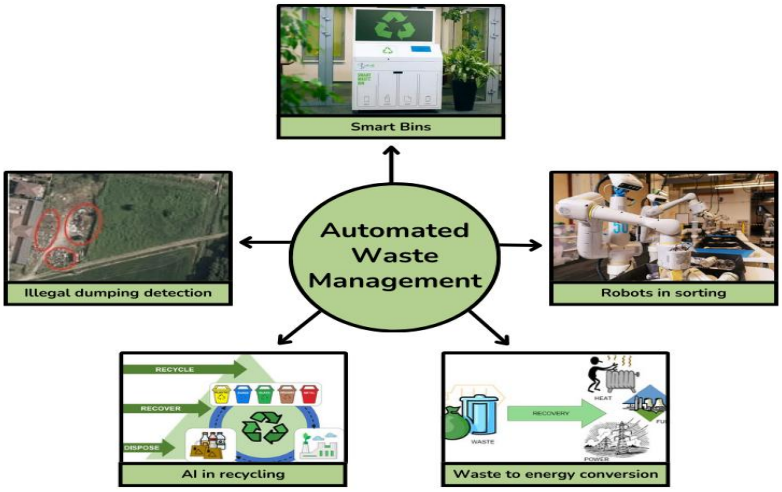

Figure: 2. Different ways for Automated Waste Management

How AI Helps in Making Economic and Policy Decisions

AI-driven analytics help policymakers plan waste-to-energy projects efficiently. Identifies cost-effective locations for WTE plants based on waste availability and energy demand.AI helps cities and industries achieve sustainability goals by providing real-time data on waste reduction and energy recovery.

Citizen Engagement & Smart Apps

AI-powered smart apps and digital platforms are making waste management more efficient and user-friendly (Wolniak and Grebski, 2023). These apps encourage proper waste disposal, improve recycling rates and optimize waste collection services.

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Table: 1. AI Powered Smart Apps

Rubicon App	RUBICON	Uses AI to help cities track waste collection and recycling performance.
Recycle Coach	recycle coach RECYCLEBN.ORG	Helps users determine whether an item is recyclable or not.
ClearWaste		Helps users find local recycling centres and book waste collection.
RecycleBank	RECYCLE BANK	Rewards users for recycling with discounts at local stores.
ECO coin		Rewards users for recycling with discounts at local stores.
Litterati		Uses AI to track and analyse litter trends.
SeeClickFix	SeeClickFix	Enables citizens to report public waste issues to local authorities.
TrashOut	TrashOut	A global app that maps and tracks illegal waste dumping.
My Little Plastic Footprint	My Little Plastic Footprint	Encourages users to track and reduce plastic waste.
Back Market	Back Market	A market place for refurbished electronics.
Thredup	THREDUP	A second-hand clothing marketplace.
Olio	OLIO The Food Sharing Revolution	A food-sharing app that prevents waste by connecting neighbours and businesses.
Too Good To Go		Allows people to buy surplus food from restaurants at a discount.
Sensoneo	((S))	Uses smart sensors to monitor waste levels and optimize collection routes.
Bin-e	Bin-e	A smart bin that automatically sorts waste into recyclables and non-recyclables.

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Circular Economy

The circular economy is an economic framework that focuses on cutting down on waste and get the most out of resources. It's different from the traditional linear economy which follows a "take, make, throw away" pattern (Salmenperä etal., 2021). Instead a circular economy tries to retain products, materials, and resources utilized for the prolonged use. The core principles of a circular economy involve designing durable products that are easy to repair and upgrade. Cutting down on waste as lowering waste through better design and recycling and using resources well by applying resources in a way that's less harmful to the environment and adds more value over time.

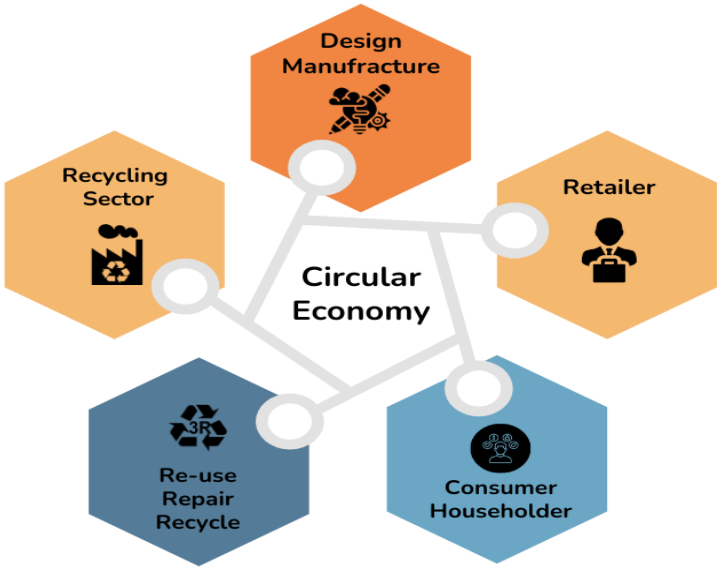

Figure: 3. Economic Framework of Circular Economy

Conclusion:

Waste management automation is a major move towards promoting a circular economy. With the inclusion of technologies like robotics, artificial intelligence, sensors, and intelligent waste sorting systems, the waste collection, sorting, recycling, and disposal processes can be significantly improved. Automation results in less human interacti on, better use of resources, and fewer errors, which contributes to increased recycling rates and less landfill reliance. As automation of waste management continues, it facilitates the conversion of waste into useful resources in line with circular economy principles. This shift not only saves natural resources but also encourages sustainability, minimizes e nvironmental pollution and supports economic growth through the establishment of new business models and opportunities. In the end, automation speeds up the shifts to a more sustainable, resource-efficient and eco-friendly future setting the pace for circular economy practices across sectors.

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