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10. Circular Practices for Waste Reduction: Strategies, Technologies and Policy Perspectives

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Abstract

Efficient waste management is pivotal in navigating the environmental challenges posed by modern urbanization and consumerism. This review paper delves into the complexities of waste management and elucidates a synchronized strategy that intertwines technological advancement, policy restructuring, community engagement, and the principles of a circular economy. Despite formidable challenges such as escalating urbanization, requisite public participation, and the integration of advanced technologies, there exist substantial opportunities to refine waste management practices. Innovation, economic incentives, and collaborative endeavors emerge as key drivers in the evolution towards more sustainable, efficient, and resilient waste management systems. This paper advocates for a concerted effort among various stakeholders including governments, industries, communities, and individuals to foster a sustainability-centric culture, incentivize recycling and waste reduction, and invest in cutting-edge technologies. Emphasizing the incorporation of circular economy principles into waste management strategies, this review highlights the potential to address waste issues comprehensively while contributing to broader sustainability goals such as resource conservation, greenhouse gas emission reduction, and economic growth. The pursuit of enhanced waste management is an ongoing journey fraught with challenges, yet the envisioned future benefits of an eco-friendly approach are substantial. Through collective action, continual innovation, and a steadfast commitment to sustainability, waste management can transcend its traditional boundaries, becoming a cornerstone for fostering a healthier planet and a thriving society for generations to come.

Keyword- Circular Practices, Waste Reduction, Technologies, Policy Perspectives

Introduction

In an era when the world population has risen to 8.1 billion, the rapid expansion is putting unprecedented strain on our planet's resources. This demographic expansion is directly linked to a rise in demand for everyday products and food packaging, which in turn increases municipal garbage generation. With disposal places dwindling, the burgeoning waste dilemma not only poses serious environmental consequences but also has important implications for human health and animals (Fig 1) [1]. The majority of garbage is disposed of in open places, creating a source of toxic gases that contribute to air pollution and various ailments (Fig 2). [2] In addition, rainwater that seeps through these waste disposal sites becomes a hazardous mixture, posing a threat to the quality of both surface and underground water by releasing harmful chemicals. Open dumping, a widespread waste management practice, is not only visually unappealing but also a huge environmental threat, as it disperses pollutants across extensive regions and worsens pollution. In the face of these difficulties, the idea of a circular economy arises as a promising solution, promoting a fundamental change in our methods of production, use, and disposal of commodities.[3] The regenerative paradigm, in striking contrast to the usual linear 'take-make-dispose' strategy, aims to minimise waste by continuously utilising resources. The concept of a circular economy focuses on designing products that are durable, can be reused, remanufactured, and recycled. This approach tries to minimise waste production, encourage innovation, and create economic opportunities in the recovery of materials and sustainable product design[3], [4]. Circular practices in waste reduction encompass a wide range of methods, technologies, and policy interventions that can be applied to various sectors, such as industrial manufacturing, municipal solid waste management, and consumer products production. These methods are based on ideas such as waste prevention, eco-design, and industrial symbiosis, with the overall goal of reducing waste generation at its origin [5]. The urgent necessity for waste reduction is especially evident in industries such as pharmaceuticals and specialty chemicals, where intricate manufacturing processes and strict purity standards result in substantial waste creation. To tackle these challenges, it is crucial to employ innovative methods that utilise advanced optimisation techniques and can effectively handle different types of waste streams. Linninger et al. (2000) emphasised the importance of flexibility in this regard. China's municipal solid waste (MSW) sector is currently experiencing a significant change. The country is moving away from traditional landfilling practices and adopting more sustainable alternatives such as incineration and biological treatment. This movement is primarily driven by government policies and expenditures in sanitation infrastructure [6].

The pursuit of a circular economy and efficient waste reduction requires the cooperation of policymakers, industry players, and the community. This review will examine the specific circular practices applied in different industries, focusing on the tactics, technologies, and policies that support successful waste reduction. The assessment seeks to shed light on the route towards achieving more sustainable waste management and environmental stewardship by analysing these practices. It emphasises the crucial role of a circular economy in solving the problems posed by the rapid growth of our population and the resulting trash crisis[7].

Fig 1.1 Garbage Mountain in the area of Delhi (Source Wikipedia)

1. Conceptual Framework for Circular Practices in Waste Reduction

The theoretical framework for implementing circular practices in waste reduction is based on the transformation from a linear to a circular economy, a fundamental change necessary for attaining sustainable waste management. This framework not only focuses on the technical components of waste reduction, but also includes the economic, social, and policy factors. It offers a comprehensive approach to efficiently managing resources and minimising waste[8].

Linear vs. Circular Economy

Historically, the global economy has functioned based on a linear model that involves the process of taking resources, manufacturing products, and then disposing of them. This model involves the extraction of resources, their conversion into products, their use, and their eventual disposal as trash, resulting in a unidirectional movement of materials. This method has led to substantial environmental deterioration, depletion of resources, and heightened output of trash[9]. On the other hand, a circular economy suggests a regenerative system in which the value of products, materials, and resources is preserved for as much time as feasible. The minimization of waste and resource use is achieved by completing the loops of product lifecycles through the processes of recycling, reusing, remanufacturing, and refurbishment. This shift not only decreases waste and environmental harm but also provides economic advantages by generating new prospects for sustainable resource utilisation[10].

Principles of Circular Economy

The circular economy is built on three core principles:

Design Out Waste and Pollution: By reconsidering resource utilisation, products can be intentionally designed to minimise waste and mitigate their environmental footprint. This entails the careful choice of sustainable materials, the utilisation of environmentally friendly manufacturing methods, and the guarantee that products may be effortlessly dismantled for recycling or repair purposes.[11].

Keep Products and Materials in Use: Optimising the utilisation of products and materials helps to maintain their worth and minimises the requirement for additional resources. These

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objectives can be accomplished by implementing tactics such as repair, refurbishment, remanufacturing, and designing items that possess durability and are simple to maintain[12], [13].

Regenerate Natural Systems: A circular economy not only seeks to reduce waste, but also strives to improve natural systems by reintroducing valuable nutrients into the environment and promoting biodiversity. This principle acknowledges the interdependence of human and ecological well-being and promotes the adoption of methods that renew and rehabilitate ecosystems[14].

Implementation Strategies

To operationalize the circular economy, several strategies can be employed across different sectors:

Product as a Service: This model emphasises service provision over product ownership, encouraging users to lease or share products. As a result, it reduces the demand for new items and promotes the efficient use of resources[15], [16].

Industrial Symbiosis: Companies in close proximity engage in collaborative efforts by using the waste or byproducts generated from one process as the raw materials for another operation. This creates a network of exchanges for materials and energy, resulting in a reduction of overall waste[16].

Resource Recovery: Advanced technologies are employed to recover resources from waste streams, transforming them into valuable materials or energy, thus reducing landfilling and incineration.

Eco-design: Products are meticulously built to consider their complete lifecycle, with a specific emphasis on minimising environmental harm by carefully selecting materials, prioritising energy efficiency, and ensuring ease of recycling or repair[17, pp. 2004–2019].

Policy and Stakeholder Engagement

Facilitating the shift towards a circular economy necessitates the implementation of favourable policies and the active involvement of stakeholders from all sectors. Governments can have a crucial impact by enacting policies that encourage circular behaviours, such as extended producer responsibility and waste reduction targets. Enterprises have the ability to introduce novel ideas in terms of product design and business strategies, while individuals can actively participate by choosing environmentally-friendly items and doing recycling and conservation activities[17, pp. 2004–2019], [18].

Metrics and Measurement

In order to monitor progress and assess the efficiency of circular activities, it is crucial to have reliable metrics and measurement methods. These indicators can encompass factors such as resource consumption, waste creation, recycling rates, and the environmental implications throughout the lifecycle of products. Through the process of quantifying the advantages of

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circular practices, individuals or groups with an interest in the matter can make well-informed choices and consistently enhance their methods for reducing waste[19], [20].
Essentially, the conceptual framework for circular practices in waste reduction promotes a fundamental change from linear resource use to a circular model. This approach focuses on innovative design, collaboration across sectors, and involvement of all stakeholders to achieve sustainable waste management and resource conservation.
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Circular Practices for Waste Reduction

Waste Reduction in Pharmaceutical and Specialty Chemical Industries

The pharmaceutical and specialty chemical sectors play a crucial role in the worldwide economy, supplying vital products for healthcare, agriculture, and diverse industrial uses. Nevertheless, these industries also make substantial contributions to industrial waste, mainly because of their intricate manufacturing procedures and the strict quality standards imposed on their goods. The adoption of circular practices in these industries is crucial not only for the preservation of the environment but also for achieving resource efficiency and economic resilience[21], [22].
Process optimization: Improving process efficiency and minimising side reactions can decrease waste production at its origin. Advanced methodologies such as process analytical technology (PAT) and the principles of green chemistry play a crucial role in this matter.

Material recovery and recycling Implementing closed-loop systems for solvent recovery and material recycling in manufacturing processes can significantly reduce waste. This approach not only decreases the negative effects on the environment but also provides financial advantages by reducing the expenses associated with resource consumption.

Collaboration for waste reduction: Industrial symbiosis, a process in which waste or by-products from one firm are utilised as raw materials by another company, has the potential to stimulate creative waste reduction strategies and improve the efficient use of resources in industrial clusters.
By implementing these tactics, the pharmaceutical and specialty chemical sectors can effectively decrease their waste production, so promoting environmental sustainability. Additionally, they can attain economic benefits by optimising resources and ensuring compliance with regulatory requirements.

Municipal Solid Waste (MSW) Management

Effective management of Municipal Solid Waste (MSW) is a crucial component of urban planning and the promotion of environmental sustainability. Efficient management of municipal solid waste (MSW) encompasses the gathering, processing, and elimination of garbage produced by residential areas, commercial establishments, and public areas. Due to increased urbanisation and population growth, cities around the world are encountering more difficulties in effectively managing the growing amounts of municipal solid waste (MSW)[23], [24] different type of and there recyclability mention in Table 1.

Key Components of MSW Management:

Efficient garbage collection systems are crucial for preventing littering, minimising environmental contamination, and managing vermin. Implementing segregation at the point of origin and implementing separate collection of recyclable and organic trash can greatly improve the effectiveness of future waste treatment procedures. Waste treatment encompasses a range of techniques aimed at minimising, reusing, and recycling waste materials. Typical therapy approaches consist of:
Recycling involves the act of segregating and treating materials that can be reused in order to produce new items Composting and anaerobic digestion involve the conversion of organic waste into compost or biogas, which can be utilised as fertilisers or sustainable sources of energy Incineration is the process of burning waste at elevated temperatures in order to decrease its size and generate energy. However, it is important to regulate the pollutants that may be generated during this approach.
Disposal: The ultimate disposal of garbage, usually in landfills, should only be considered as a final option because of the consequential environmental effects, such as the release of greenhouse gases and the potential pollution of groundwater. Contemporary landfills are designed to minimise these effects, but it is more desirable to employ measures that decrease waste production and enhance recycling and recovery. Ultimately, the management of MSW requires a comprehensive approach that encompasses various aspects, including technology, regulations, and human behaviour. Cities may mitigate the environmental impacts of trash, conserve resources, and create more sustainable urban environments by implementing integrated waste management systems that prioritise waste reduction, recycling, and recovery[25]

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Fig 2 Most of the open dumping animal attract towards the food waste (Source Wikipedia).

Table 1. Different types of wastes and their recyclability

Type	Characteristics	Recyclability	Items Considered	Source/Origin	Management Strategy(s)
Paper/Cardboard	Combustible when dried, biodegradable when wet	Recyclable	Papers, packages, cartons, wrappers, cardboards	Lecture rooms, offices, photocopying centers, mini-markets	Source separation, Reusable, Recyclable, Energy Generation
Garbage	Organic, biodegradable, combustible when dried	Recyclable	Food leftovers, peels, bread, dead animals	Hostels, kitchens, restaurants	Composting, Energy Generation, Feed for Livestock, Source Separation
Plastics, Polythene, Packaging Foils	Non-biodegradable, residue hardly decays when burnt	Recyclable	Cans, bags, bottles, syringes, plastic chairs	Markets, medical centers, laboratories	Recyclable
Metals/Junks	Neither combustible nor biodegradable	Recyclable	Automobile junks, metal utensils, scrap electronics	Work departments, markets, hostels	Recyclable, Reusable, Source Separation
Ashes	Non-combustible, biodegradable	Non-recyclable	Burnt wood, charcoal, burnt paper	Quarters, hostels, offices	Soil treatment, Source Separation
Rags	Combustible, not biodegradable	Recyclable	Cloths, threads,	Quarters, hostels,	Recyclable, Reusable,

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			cotton, nylon	tailoring shops	Source Separation
E-Waste	Non-biodegradable, some parts combustible	Recyclable	Electric cables, printers, phones	Quarters, hostels, commercial areas	Reusable, Recyclable, Source Separation
Leather	Combustible, not biodegradable	Recyclable	Leather shoes, bags	Quarters, hostels	Reusable, Recyclable
Sanitary Waste	Non-biodegradable	Non-recyclable	Pads, diapers, cotton wools	Quarters, hostels	Hygienic Disposal

Technological Advances and Management Optimization

In the realm of waste management, technological advancements and management optimization play pivotal roles in enhancing efficiency, reducing environmental impact, and facilitating the transition towards more sustainable practices. These innovations are instrumental in addressing the complexities of waste collection, segregation, recycling, and disposal, thereby propelling the industry towards circular economy goals[25], [26], [27], [28].

Smart Waste Management: IoT-enabled bins and collection systems optimize routes and schedules, reducing costs and emissions.

Advanced Recycling Technologies: AI and robotics enhance the sorting and recycling of materials, increasing recycling rates and efficiency.

Waste-to-Energy: Technologies like pyrolysis convert waste into energy, reducing landfill use and generating renewable energy.

Biological Treatment: Enhanced composting and anaerobic digestion processes convert organic waste into compost or biogas, supporting soil health and renewable energy.

Optimizing management involves:

Data-Driven Decisions: Analytics improve operational efficiency and guide waste reduction and recycling strategies.

Policy Support: Robust regulations incentivize sustainable practices and ensure environmental compliance.

Stakeholder Engagement: Involving communities and businesses in waste management fosters shared responsibility and enhances program effectiveness.

Supply Chain Integration: Incorporating circular principles reduces waste generation and promotes product sustainability. Together, these technological and managerial advancements are pivotal in advancing waste management towards greater sustainability and alignment with circular economy goals different study and management mention in Table 2.

Table 2 Different studies with their recommended strategies for the major wastes

Source	4 major Categories investigated with percentages	Recommended Strategies
Uwadiae et al. [29]	Organic (30.22%) Plastics/Rubber/ Polythene (26.67%) Paper (18.65%) Metals (11.08%) Recyclable (59.9%)	The specific strategies were not detailed in the provided text, so I'm assuming it includes various forms of recycling and possibly other forms of waste management strategies.
Armijo De Vega et al. [30]	Organic (48.1%) Paper/cardboard (24.8%) Plastic (6%) Recyclable (76%)	Recommended the use of organic and garden wastes in compost production to support reforestation and maintain green areas. Advocated for electronic communication channels, repackaging mails in brown envelopes, internal memos on unused paper sides, and photocopying/printing on both paper sides.
Sepideh et al. [31]	Organic (45.3%) Plastic (19.23%) Paper (14.45%) Glass (8.87%)	Suggested using garden waste for composting for reforestation and green area preservation. Recommended using organic waste as feedstock for animals, substituting plastics with special glass cups, implementing sustainable recycling for plastics, and educating about paper use and recycling. Emphasized waste source separation and periodic waste characterization studies.
Okeniyi and Anwan [32]	Food waste (26.29%) Plastic bags/food packs (20.88%) Polythene (19.37%) Metal cans (11.59%) Paper (10.52%)	Recommended a bio-gasification scheme for biogas and compost production. Suggested employing co-incineration, gasification, and pyrolysis for non-biodegradable waste reduction and sanitary landfill systems for disposal, integrating these with other strategies for sustainable waste management.
Chee & Sumiani [14]	Food waste (40%) Mixed papers (14%) Plastic waste (20%) Polystyrene and PET bottles (8%)	Noted the collection of food waste for animal feed and recommended replacing soil conditioners with compost. Mentioned an ongoing Takakura composting project and informal paper recycling. Proposed reusing unused paper sides, double-sided printing, and

		source separation to avoid contamination. Highlighted campaigns like "No Polystyrene" and encouraged using PET bottles and reducing plastic bags.
Sreedevi [33]	Organic (24%) Paper (14.7%) Plastic (8%) Glass (3.3%)	Advocated for waste source separation, especially to prevent organic waste contamination. Recommended community-level organic waste collection for composting and economic recycling of non-degradable wastes. Emphasized government-led awareness and education programs for waste segregation and recycling promotion.
Aragaw et al. [34]	Paper/Cardboard (31%) Organics (23%) Plastics (16%) Construction/ Demolitions (14%) Compostable (57.43%) Recyclable (38.93%)	Highlighted waste management achievements at Bahir Dar Institute of Technology through integrated solid waste management, waste prevention, consistent training, and promoting composting, reusing, and recycling.
Coker et al. [35]	Paper (35%) Organic (29%) Plastics & nylon (12%) Metal (10%)	Suggested paper reuse, organic waste decomposition through anaerobic digestion and composting for bioenergy and fertilizer production. Recommended regular waste management campaigns, community education, and best practice sensitization.
Dangi and Agarwal [36]	Organic (47%) Paper (18.13%) Plastic (12.29%)	Recommended organic waste composting and vermicomposting for soil enrichment, garden waste conversion to charcoal and biomass briquettes, and paper waste recycling in producing file covers, egg trays, and cartons. Suggested restoring the institution's paper recycling plants.
Adeniran et al. [37]	Polythene (24%) Organic (15%) Paper (15%) Plastic (9%) Recyclable (75%)	Similar to Ugwu et al., it suggested compost production from organic waste for soil enrichment, energy generation, and optimization with sewage systems. Highlighted a university practice of a paperless policy, online official activities, and direct paper recycling by staff. Recommended water dispensers to reduce polythene and plastic waste and supported policies for sustainable water and waste management.

Al-Salem et al. [38]	Plastics (100%)	Reviewed various recycling and recovery routes for plastic solid waste (PSW), including mechanical recycling, feedstock recycling, and energy recovery. Identified opportunities for improving recycling rates and reducing plastic waste in university campuses through enhanced collection systems and collaboration with recycling facilities.
Das et al. [39]	Organic Waste (40%), Paper (30%), Plastics (20%), Others (10%)	Discussed solid waste management practices in educational institutions, including universities. Recommended source segregation, composting of organic waste, paper recycling initiatives, reduction of single-use plastics, and awareness campaigns to promote sustainable waste management behaviors among students and staff.
Kumar et al. [40]	Organic Waste (30%), Plastics (25%), Paper (20%), Others (25%)	Reviewed technological options for waste-to-energy conversion from municipal solid waste (MSW), including anaerobic digestion, incineration, and pyrolysis. Recommended the implementation of waste-to-energy facilities on university campuses to manage organic waste effectively and reduce the environmental impact of landfilling.
Adhikri el al. [4]	Plastic (40%), Paper (25%), Organic Waste (20%), Others (15%)	Reviewed the solid waste management system in a university campus setting as a case study. Recommended the adoption of a comprehensive waste management plan incorporating segregation at source, recycling initiatives for plastics and paper, composting of organic waste, and the establishment of a waste-to-energy plant to manage residual waste effectively.
Ezeah et al. [41]	Plastics (50%), Paper (30%), Metals (10%), Others (10%)	Examined emerging trends in informal sector recycling in developing countries. Recommended collaboration between universities and informal sector recyclers to improve recycling rates, establishment of collection points for recyclables on campuses, and awareness campaigns to promote recycling among students and staff.
Aderin et al. [37]	Organic Waste (45%), Paper (25%), Plastics (15%), Others (15%)	Investigated waste generation and composition in households, with implications for waste management in universities. Recommended the implementation of waste audits on campuses to

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	understand waste composition, development of tailored waste management strategies targeting organic waste, paper recycling, reduction of single-use plastics, and community engagement initiatives.

Challenges and Opportunities in Waste Management

Rapid Urbanization and Consumption: Increasing urban populations and consumerism lead to higher waste generation, straining existing waste management infrastructure[42].

Technological Implementation: While advanced technologies offer significant benefits, the high costs and technical complexities involved in their implementation can be major barriers, particularly in less developed regions[43].

Public Awareness and Participation: Achieving high levels of community participation in waste segregation and recycling programs remains a challenge. Behavioral change is crucial but often difficult to instigate and sustain[44].

Policy and Regulation: Inconsistent or weak regulatory frameworks can hinder the effective enforcement of waste management practices. There's also a need for policies that adapt to technological advancements and evolving waste management paradigms[45].

Recycling Market Fluctuations: The viability of recycling can be affected by market demand for secondary materials. Price volatility can discourage investment in recycling infrastructure[46].

Innovation and Technological Advancement: The continuous evolution of smart technologies and waste-to-energy solutions presents opportunities to enhance efficiency and sustainability in waste management[47].

Economic Incentives: By incentivizing recycling and waste reduction, governments can stimulate market development for recycled materials and promote investment in waste management infrastructure[35].

Circular Economy Integration: Adopting circular economy principles offers a systemic approach to minimizing waste and maximizing resource use, fostering sustainable production and consumption patterns[48].

Public Engagement and Education: Educating the public and involving communities in waste management processes can improve waste segregation, increase recycling rates, and foster a culture of sustainability[49].

Collaborative Efforts: Partnerships between governments, industry, academia, and civil society can drive innovation, share best practices, and scale successful waste management models[50], [51], [52].

Conclusion

Efficient waste management is a complex problem that necessitates a synchronised strategy, integrating technical advancement, policy restructuring, community involvement, and the implementation of circular economy principles. Although the problems are considerable, including rising urbanisation, the requirement for public engagement, and the incorporation of sophisticated technologies, they can be overcome. There are many opportunities to improve waste management techniques by using innovation, economic incentives, and collaboration. This will result in more sustainable, efficient, and resilient systems. Seizing these opportunities necessitates a coordinated endeavour from all parties involved, such as governments, industries, communities, and individuals. By cultivating a culture that prioritises sustainability, providing incentives for recycling and trash reduction, and allocating resources to advanced technology, we can effectively diminish the ecological consequences of waste. In addition, incorporating circular economy ideas into waste management strategies provides a means to not only tackle trash problems but also contribute to wider sustainability objectives, such as conserving resources, reducing greenhouse gas emissions, and promoting economic growth. The pursuit of enhanced waste management is a continuous endeavour, and although obstacles persist, the potential advantages of a more environmentally friendly strategy are evident. Through joint efforts, ongoing innovation, and a focus on sustainability, we have the potential to revolutionise waste management and make it a significant driver of a healthier planet and a more prosperous society for future generations.

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