CLOSING THE LOOP

TRANSFORMING INDIA'S SOLID WASTE SECTOR THROUGH CIRCULAR ECONOMY FRAMEWORK

POLICY-ORIENTED TECHNICAL REPORT

CSIR-NATIONAL ENVIRONMENTAL ENGINEERING RESEARCH INSTITUTE (NEERI), NAGPUR

April 2026

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Government of India
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Message

As India advances towards becoming a global economic leader, the challenges of resource efficiency, waste management, and environmental sustainability call for systemic and integrated solutions. The increasing complexity of waste streams and mounting resource constraints underscore the urgent need to transition towards a circular economy that enables material recovery, reduces dependence on virgin resources, and fosters sustainable and resilient growth.

Council of Scientific and Industrial Research (CSIR) has consistently played a pivotal role in delivering science-led solutions to national challenges. CSIR–NEERI stands at the forefront of India's environmental research ecosystem, driving innovations to advance sustainable

waste management and accelerate the nation's transition towards a circular economy. This Policy-oriented Technical Report adopts a holistic, systems-based approach, integrating sustainable material flows, decentralized waste management, and advanced resource recovery, while leveraging emerging technologies for data-driven governance and decision-making.

Aligned with national priorities on climate action and sustainable development, the framework emphasizes inclusivity, innovation, and collaborative models involving public and private stakeholders.

This document is expected to serve as a valuable guide for policymakers, industry, and practitioners, supporting India's transition towards a sustainable, circular, and low-carbon future. I extend my best wishes for its successful adoption and impactful implementation.

April 4, 2026

New Delhi

(N. Kalaiselvi)

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Preface

It is my privilege to present "Closing the Loop: Transforming India's Solid Waste Sector through Circular Economy Framework," a policy-enabling document that seeks to redefine the future of India's resource management and environmental sustainability by Dr. Debishree Khan, Senior Scientist, CSIR-NEERI.

At a time when rapid urbanization, industrial growth, and resource constraints are placing immense pressure on ecosystems, this framework offers a pathway to transition from a linear "take–make–dispose" model to a circular economy. It redefines waste as a resource, enabling environmental protection, resource efficiency, and economic opportunity, while aligning with India's climate and sustainability goals. The report integrates policy, technology, and governance to accelerate decarbonization and promote sustainable consumption. Its systems approach combines decentralized waste management, advanced resource recovery, and digital innovation. The proposed digital platform, leveraging AI, IoT, and blockchain, enhances transparency and decision-making. It also emphasizes inclusive growth by engaging the informal sector, strengthening public-private partnerships, and supporting circular entrepreneurship.

I am confident that this report will serve as a cornerstone in advancing India's transition towards a circular, low-carbon, and climate-resilient economy, reinforcing the nation's leadership in sustainable development while delivering long-term environmental, economic, and societal benefits.

April 4, 2026
Nagpur

(S. Venkata Mohan)

Executive Summary

At CSIR-NEERI, we believe sustainable development requires transformative frameworks that blend scientific rigor with practical action. “Closing the Loop: Transforming India’s Solid Waste Sector through Circular Economy Framework” embodies this vision, providing a comprehensive roadmap to integrate circular economy principles into India’s developmental agenda. This framework transitions from the linear “take-make-dispose” model to a regenerative system that prioritizes resource efficiency, minimizes waste, and mitigates greenhouse gas (GHG) emissions, aligning with India’s commitments under the Paris Agreement and Nationally Determined Contributions (NDCs). By integrating waste management with climate goals, it fosters a low-carbon economy critical for sustainable growth.

The framework conducts a thorough analysis of key waste streams—municipal solid waste, plastics, e-waste, construction and demolition debris, industrial by-products, agricultural waste, and biomedical waste. It proposes targeted interventions, such as decentralized waste management and resource recovery, to unlock significant environmental and economic benefits. A central pillar is a national digital platform leveraging advanced technologies like AI, IoT, and blockchain to enable real time waste tracking, resource exchange, and compliance monitoring. This platform ensures transparency, predictability, and efficiency across the waste value chain, enhancing collaboration among stakeholders.

“Closing the Loop” advocates innovative circular business models focused on reuse, recycling, and resource optimization, supported by policy reforms and financial mechanisms to drive systemic change across sectors. These strategies are designed to create scalable, sustainable solutions tailored to India’s diverse socio-economic context. CSIR-NEERI’s expertise in environmental research and innovation underpins these approaches, ensuring they are both practical and impactful.

Beyond technical solutions, the framework emphasizes capacity building, stakeholder engagement, and policy advocacy to accelerate India’s transition to a circular economy. It calls for collaboration among government, industry, academia, and civil society to build skills, raise awareness, and implement context-specific solutions. The framework provides a quantifiable roadmap for GHG mitigation, with clear short-, medium-, and long-term recommendations to ensure measurable progress toward sustainability.

Serving as both a strategic guide and a call to action, “Closing the Loop” positions circular economy principles at the heart of India’s green growth agenda. By leveraging innovation, collaboration, and CSIR-NEERI’s expertise, it charts a transformative path toward a sustainable, climate-resilient future, addressing pressing environmental challenges while unlocking economic opportunities for India.

List of Abbreviations

3R – Reduce, Reuse, Recycle
AI – Artificial Intelligence
ANN – Artificial Neural Networks
ASHA – Accredited Social Health Activists
BMW – Biomedical Waste
C&D – Construction and Demolition
CBWTF – Common Biomedical Waste Treatment Facilities
CE – Circular Economy
CII – Confederation of Indian Industry
CITI – Confederation of Indian Textile Industry
CNN – Convolutional Neural Networks
COP – Conference of the Parties
CPCB – Central Pollution Control Board
CSIR-NEERI – Council of Scientific and Industrial Research – National Environmental Engineering Research Institute
CSIRO – The Commonwealth Scientific and Industrial Research Organisation
CSR – Corporate Social Responsibility
DT – Decision Trees
EPA – Environmental Protection Agency
EPR – Extended Producer Responsibility
EU – European Union
EV – Electric Vehicle
FAO – Food and Agriculture Organization
FICCI – Federation of Indian Chambers of Commerce and Industry
FMCG – Fast Moving Consumer Goods
FSSAI – Food Safety and Standards Authority of India
GDP – Gross Domestic Product
GHG – Greenhouse Gas
GIS – Geographic Information System
GN – Genetic Algorithms
GPS – Global Positioning System
HWTS – Hazardous Waste Tracking System
ICAR – Indian Council of Agricultural Research
IEA – International Energy Agency
IFC – International Finance Corporation
IoT – Internet of Things
IPCC – Intergovernmental Panel on Climate Change
M&E – Monitoring and Evaluation
MLP – Multilayer Perceptron
MNRE – Ministry of New and Renewable Energy
MoEFCC – Ministry of Environment, Forest and Climate Change
MoHUA – Ministry of Housing and Urban Affairs
MRF – Material Recovery Facility
MSME – Micro, Small, and Medium Enterprises
MSW – Municipal Solid Waste
NCEF – National Circular Economy Framework
NDCs – Nationally Determined Contributions
NGO – Non-Governmental Organisation
NIUA – National Institute of Urban Affairs
NITI – National Institution for Transforming India
OWC – Organic Waste Converter
PaaS – Product-as-a-Service
PPP – Public-Private Partnership
PPE – Personal Protective Equipment
PV – Photovoltaic
PWM – Plastic Waste Management
RDF – Refuse-Derived Fuel
RENEU – Restoring Polluted Nallahs into Ecologically Usable Streams
RFID – Radio Frequency Identification
SDGs – Sustainable Development Goals
SME – Small and Medium Enterprises
SOP – Standard Operating Procedures
SPCB – State Pollution Control Board
SUP – Single-Use Plastics
SVM – Support Vector Machines
SWM – Solid Waste Management
TERI – The Energy and Resources Institute
TPA – Tons per Annum
TPD – Tons Per Day
TSDF – Treatment, Storage, and Disposal Facility
UCCW – Upflow Compact Constructed Wetland
ULB – Urban Local Bodies
UNEP – United Nations Environment Programme
W2B – Waste to Biofuels
WHO – World Health Organization
WRAP – Waste and Resources Action Programme
WtE – Waste-to-Energy

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1 Introduction

In the twenty-first century, developing countries including India face a wide range of difficult issues, from urbanization, political unrest, and fast population increase to food and water shortages, environmental damage, infectious diseases, and climate change. Resilience is crucial at all societal levels in this dynamic and unpredictable environment, from local communities and rural households to government agencies and major companies. A dual strategy is required to achieve resilience: progressive government policies combined with creative social and environmental projects that show flexibility in the face of adversity. Such programs can operate as useful models for developing a more robust and sustainable Indian economy, as Fiksel et al. (2021) point out. The adoption of circular economy solutions, which prioritize the effective use of resources and the removal of waste, is one of the most promising prospects to hasten this shift. According to the Circularity Gap report, 2021, only 8.6% of the global economy is circular, which means that the majority of materials are still derived from virgin sources (Circle Economy, 2021). More recent updates show that this value has been dropped to 6.9%, which highlights a declining trend. Improving circularity is essential to reducing out resource extraction and attaining climate targets, such as keeping global warming far below the Paris Agreement's 2°C limit. This will aid in reducing global emissions by around 39%. Circular economy techniques can assist in reducing environmental effects while fostering economic growth and resource efficiency by re-evaluating conventional waste management procedures and using creative methods for recycling abandoned materials. The move toward circularity can be extremely important in tackling sustainability issues in India, as waste creation is rising in tandem with the country's fast urbanization. It can also support more comprehensive climate action and economic resilience. Despite their close relationship, resilience and sustainability are different in scope and time frame. Resilience is a more immediate idea that emphasizes adaptation to unexpected events, whereas sustainability concentrates on long-term well-being and strives for harmony between humans and the environment. Although these ideas frequently support one another, there are instances where they are at odds, such as when resource stockpiling improves resilience but has a negative impact on the environment. In India, accomplishing both calls for a well-rounded strategy that combines progressive governmental policies with creative social and environmental projects. India can set the path for a robust and sustainable economy that can handle the challenges of the twenty-first century by embracing systems thinking and useful models (Fiksel et al., 2021).

A well-designed circular economy must be inclusive, guaranteeing that management choices consider the effects on all parties involved, especially marginalized and vulnerable communities impacted by the growth of waste. Businesses can reduce waste profitably while simultaneously promoting social well-being and public trust by placing a high priority on the management of natural and social capital. In addition to benefiting shareholders, efficient management of municipal, agricultural, and industrial waste advances environmental and economic resilience and supports a number of UN Sustainable Development Goals.

Authorities have been compelled to switch from the conventional linear take-make-use-dispose method of resource conservation to a circular system due to the rapid depletion of resources and growing urbanization. Reduce, reuse, recycle, and recover is the waste management method that is the focus of the circular economy (CE), a sustainable development concept (Kakwani et al., 2020).

The circular economy presents an opportunity for sustainable economic growth by shifting towards a model that is **resilient, diverse, and inclusive**. It aims to reduce the use of natural resources through CE principles, which will aid in the reuse/ recycle of waste, consequently regenerate natural systems, and keep materials in use, addressing critical global challenges such as **climate change, biodiversity loss, and pollution**. Governments and industries worldwide are increasingly adopting circular economy strategies to accelerate this transition, integrating them into climate action frameworks, policies, and business operations. Effective policymaking is essential to scale these efforts, ensuring alignment across industries and nations while reducing fragmentation in global supply chains. This approach extends beyond waste management and recycling, offering **systemic economic, environmental, and societal benefits**. For instance, it plays a crucial role in achieving the **United Nations Sustainable Development Goals**, particularly SDG 12 on **sustainable consumption and production**, and SDG 9 on **resilient industrialization and innovation**. Moreover, embedding circular economy principles in climate strategies can significantly **reduce greenhouse gas emissions** associated with production and consumption processes. Governments must take proactive steps to foster a supportive policy environment, as voluntary commitments from industries alone may not be sufficient to drive large-scale transformation. Policies that **eliminate unnecessary waste, encourage innovation, and ensure stable funding for recycling and resource recovery** are crucial. By integrating circular economy principles into national roadmaps and international commitments such as the **Paris Agreement**, policymakers can unlock long-term economic resilience and environmental sustainability (Ellen MacArthur Foundation, 2021).

To align with the principles of a circular economy and foster collaboration across industries and policymakers, the Ellen MacArthur Foundation outlines five key policy goals that can drive systemic transformation. First, stimulating design for the circular economy is essential to ensure products are designed for durability, reparability, and reuse, reducing waste and pollution. This includes policies supporting high-quality product design, circular building practices, and regenerative production. Second, managing resources to preserve value emphasizes extending product lifespans through business models promoting repair, resale, and remanufacturing, along with harmonized waste sorting, EPR policies, and reducing landfill reliance. Third, making the economics work requires economic incentives and regulatory measures to embed circular principles into taxation, subsidies, procurement, and trade policies, ensuring circular economy solutions become mainstream. Fourth, investing in innovation, infrastructure, and skills fosters research, digital and physical infrastructure, and workforce training, enabling a smooth transition. Finally, collaboration for system change highlights the need for multi-stakeholder engagement, cross-border policy alignment, public-private partnerships, and data-driven progress tracking to create a unified and durable shift toward a circular economy. These policy goals provide a structured framework for governments and businesses to collectively advance circularity, ensuring a resilient and sustainable economic future (Ellen MacArthur Foundation, 2021).

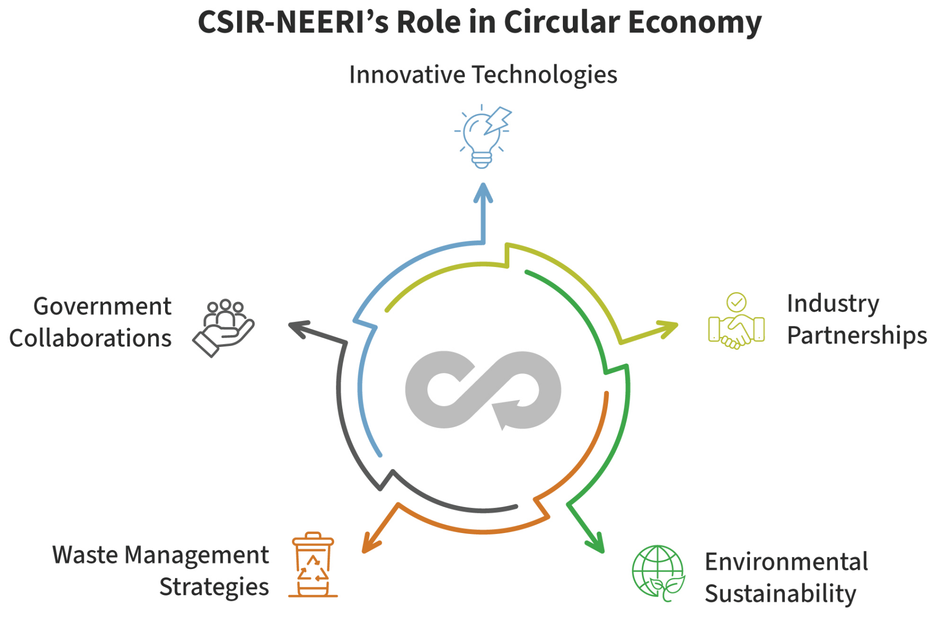


Figure 1: Role of CSIR-NEERI

CSIR-NEERI's contributions in CE

CSIR-National Environmental Engineering Research Institute (CSIR-NEERI), established in 1958 as the Central Public Health Engineering Research Institute (CPHERI) and later renamed in 1974, has been a pioneer in environmental research, particularly in waste management and circular economy solutions. Over the years, NEERI has developed innovative technologies such as Upflow Compact Constructed Wetland (UCCW) for decentralized sewage treatment, Restoring Polluted Nallahs into Ecologically Usable Streams (RENEU) for wastewater rejuvenation, and the "Waste to Biofuels (W2B)" initiative under the XII Five-Year Plan. The institute has extensively contributed to municipal solid waste management through life cycle assessment studies, municipal solid waste characterization, and landfill emissions evaluation. Its research on co-processing hazardous waste in cement kilns and valorization of plastic waste aligns with circular economy principles, reducing landfill dependency and promoting resource recovery. NEERI has played a crucial role in assessing methane emissions from waste, collaborating with MoEFCC for sustainable waste policies. Additionally, its Biotechnology Park Project focuses on converting municipal waste into biofuels, addressing both waste management challenges and energy sustainability. Through cutting-edge research, government collaborations, and industry partnerships, CSIR-NEERI continues to lead India's efforts in waste-to-resource transformation, reducing environmental pollution, and driving circular economy initiatives.

CSIR-NEERI actively promotes the principles of a circular economy. The institute's roadmap for reducing plastic waste emphasizes diverting plastic waste into resources, leading to a cleaner environment with fewer greenhouse gas emissions and improved air quality (Dhodapkar et al., 2023). In collaboration with the Indian government, CSIR-NEERI is developing a Biotechnology Park Project aimed at utilizing municipal solid waste and organic biomass as raw materials for biofuels, addressing waste management challenges cost-effectively. The institute has been at the forefront of developing sustainable solutions for municipal solid waste, hazardous waste, industrial waste, and e-waste management while emphasizing resource recovery, waste minimization, and environmental sustainability. Through its collaborations with industries, municipal bodies, and government agencies, NEERI continues to drive innovations in waste management by integrating circular economy principles. Its ongoing efforts focus on sustainable waste utilization, environmental impact assessment, and policy recommendations to support India's transition towards a resource-efficient and circular economy. Through its multidisciplinary research, technological innovations, and strategic projects, CSIR-NEERI continues to play a pivotal role in advancing waste management and fostering a circular economy in India, contributing to sustainable development and environmental conservation.

2 Gaps in Policy & Legislative Framework

India's municipal solid waste management (SWM) system has significant room for development through continuing policy and legislative change, allowing for more effective field-based implementation. Although comprehensive regulations such as the Municipal Solid Waste Management Rules, 2016 exist, they often suffer from poor enforcement, vague directives, and a lack of synchronization between planning and execution (Mani & Singh, 2016). These gaps are especially pronounced in Tier-2 and Tier-3 cities, where infrastructure is outdated, funding is insufficient, and community participation is minimal (Mishra, 2024). The following analysis highlights key problem areas and outlines actionable recommendations to bridge these gaps-

1. Weak Enforcement of Existing Regulations

Experts note that despite the existence of these laws, implementation remains woefully inadequate, with weak regulatory compliance and inadequate waste segregation being significant challenges. While national policies outline broad objectives, the lack of localized, enforceable guidelines often leads to inconsistent execution.

Recommendations

- Harmonize existing regulations to create a unified, tier-specific SWM policy.
- Empower municipal authorities with clearer mandates and adequate enforcement powers.
- Develop measurable performance benchmarks and compliance mechanisms for local bodies (SBM, 2021).

2. Disconnect Between Policy and Ground-Level Implementation

In Tier 2 cities, SWM policies are often misaligned with the realities of limited technology, workforce capacity, and funding. Despite national guidelines, many municipalities continue to use outdated waste processing methods and lack the resources to modernize (Dhaundhiyal et al., 2024).

Recommendations

- Implement decentralized waste management systems suited to smaller urban areas.
- Allocate targeted funding and training programs to enhance municipal capabilities.
- Encourage adaptive policy models that reflect ground-level challenges and innovations.

3. Insufficient Public Awareness and Participation

A lack of awareness and motivation has led to poor source segregation and low compliance with municipal rules, leading to the mixing of biodegradable and non-biodegradable waste. As a result, even well-planned systems underperform due to behavioral issues.

Recommendations

- Launch citywide awareness campaigns on waste segregation and reduction.
- Integrate environmental education into school curricula to build long-term habits.

4. Inadequate Infrastructure and Resource Allocation

Many urban local bodies struggle with inadequate infrastructure, from inefficient waste collection systems to the absence of modern treatment facilities. Financial constraints further limit their ability to adopt sustainable practices, resulting in continued reliance on landfills (Mani & Singh, 2016).

Recommendations

- Create mechanisms for sustainable financing, such as user charges and green bonds.
- Promote public-private partnerships to upgrade infrastructure and technology.
- Establish centralized procurement systems to ensure equitable access to modern equipment.

5. Overreliance on Landfills and Unsustainable Practices

Traditional waste disposal methods, particularly uncontrolled landfilling, remain common across Indian cities. These practices pose serious environmental risks, including soil and water contamination and greenhouse gas emissions (Priti & Mandal, 2019).

Recommendations

- Phase out open dumping and remediate legacy dumpsites using bioremediation techniques.
- Scale up composting, biomethanation, and waste-to-energy facilities.
- Adopt circular economy models that reduce landfill dependency through recycling and material recovery.

6. Exclusion of the Informal Waste Sector

A substantial portion of waste collection and recycling is handled by informal waste pickers. However, their exclusion from formal waste management systems leads to social and economic marginalization and poses challenges to effective waste management. The marginalization of waste pickers and their exclusion from formal waste management systems remain significant challenges in India's waste management landscape.

India's rapid urbanization and industrialization have led to significant challenges in municipal solid waste management (SWM). Despite existing policies and regulations, gaps in enforcement, infrastructure, and public participation hinder effective waste management. Addressing these gaps and transitioning towards a circular economy requires a comprehensive and robust framework.

Roadmap to Achieve a Circular Economy through a Robust Framework

In order to achieve a circular economy, a clear strategy that promotes sustainable production and consumption is necessary. Waste prevention, upcycling, recycling, and energy recovery are given priority in the CII National Circular Economy Framework, which offers this guidance. Setting the groundwork for long-term environmental and economic resilience, this roadmap aims to decrease reliance on natural assets, increase the lifespan and usefulness of materials and products, and incorporate waste-free design into all phases of economic activity.

1. Strengthening Regulatory Enforcement

Enhancing the enforcement of existing SWM regulations is crucial. This involves stringent monitoring, regular inspections, and imposition of penalties for non-compliance. Establishing dedicated enforcement agencies at the state and municipal levels can ensure adherence to waste management standards.

2. Developing Infrastructure and Allocating Resources

Investing in waste management infrastructure, including collection bins, segregation facilities, and processing units, is essential. Financial resources should be allocated efficiently, prioritizing areas with the highest waste generation. Public-private partnerships can be explored to mobilize additional resources and expertise.

3. Promoting Public Awareness and Participation

Educational campaigns and community engage-

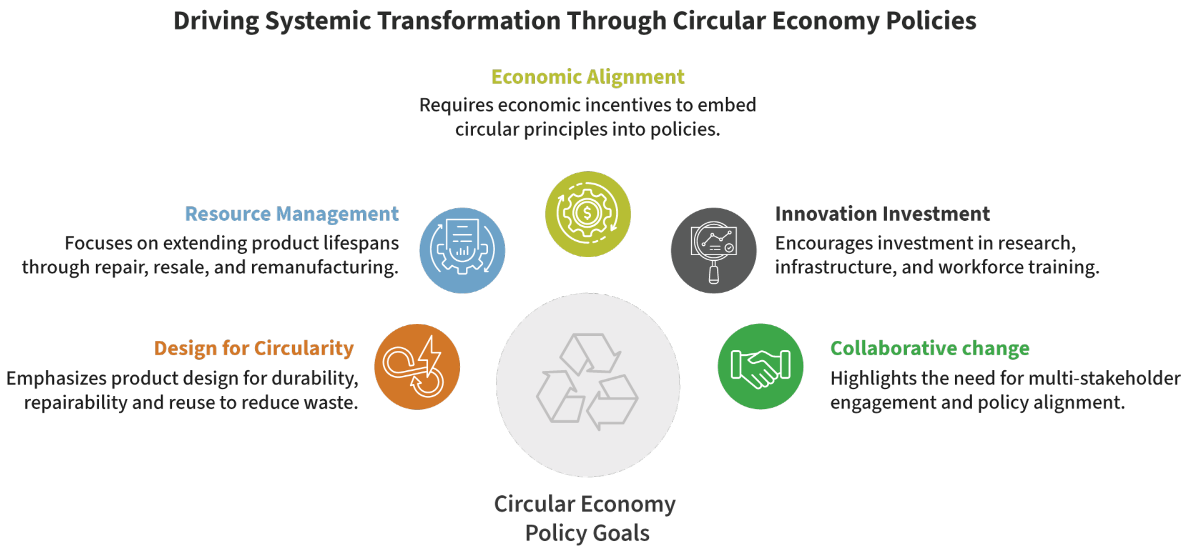


Figure 2: Circular Economy Policy Goals

ment programs can enhance public understanding of waste segregation and management. Incentivizing households and communities that practice effective waste segregation can encourage wider participation. Training programs for municipal staff and waste handlers can improve service delivery.

4. Integrating the Informal Sector

Recognizing the role of informal waste pickers and integrating them into formal waste management systems can improve efficiency and social outcomes. Providing training, fair wages, and social security benefits can uplift their status and productivity. Policies should be formulated to protect their rights and ensure their participation in decision-making processes.

5. Implementing Integrated Waste Management Strategies

Adopting a mix of centralized and decentralized waste management models, tailored to local contexts, can enhance efficiency. For instance, Goa's decentralized approach, where waste is segregated at the source and processed locally, has proven effective (NIUA, 2020; WSP, 2006). This model reduces transportation costs and promotes community involvement.

6. Transitioning to a Circular Economy

A circular economy emphasizes reducing waste, reusing products, and recycling materials. The CII has proposed a National Circular Economy Framework to guide this transition. The NCEF focuses on principles such as prevention, upcycling, recycling, and energy recovery, aiming to increase the value, use, and life of materials, products, and assets, and to design out waste from production and consumption.

Key strategies under the NCEF include

- **Material Selection:** Choosing materials based on their environmental impact and resource value potential.
- **Design for Circularity:** Encouraging product designs that facilitate reuse, repair, and recycling.
- **Extended Producer Responsibility:** Holding producers accountable for the entire lifecycle of their products, including post-consumer waste.
- **Innovation and Technology:** Promoting research and development in recycling technologies and sustainable materials.
- **Monitoring and Evaluation:** Establishing mechanisms to track progress and ensure compliance with circular economy principles.

7. Leveraging Industrial Waste Circularity

Industrial waste circularity involves reusing and recycling industrial by-products, reducing environmental impact, and promoting resource efficiency. This approach not only minimizes waste but also contributes to decarbonization efforts. However, challenges such as the lack of regulatory push and the need for stakeholder involvement must be addressed to upscale industrial waste circularity.

Addressing the gaps in India's municipal solid waste management policies and legislative framework requires a multifaceted approach that includes strengthening enforcement, filling the gaps in the EPR framework, developing infrastructure, and promoting public participation.

3 Waste Stream Analysis

3.1 Municipal Solid Waste (MSW)

Current waste generation and missing Management

Municipal Solid Waste refers to the everyday waste generated by households, commercial establishments, institutions, and public places in urban and rural areas. It includes a wide variety of discarded materials such as food scraps, paper, plastics, glass, metals, textiles, biomedical waste, hazardous, and other non-hazardous waste. MSW is commonly known as "garbage" or "trash" and is managed by municipal or local authorities. Waste management in India has long been a crucial aspect of environmental sustainability, with the SWM Rule, 2016, laying down clear guidelines for the collection, segregation, treatment, and disposal of solid waste. According to Rule 15(b) of these regulations, the responsibility of collecting segregated waste falls upon local authorities. However, the effectiveness of waste management varies across states and union territories, with gaps still existing in the overall system. India encounters significant challenges in managing its rapidly increasing waste due to rapid urbanization and economic growth. According to the latest CPCB report, India generates an estimated 1,70,339 TPD of municipal solid waste. Waste generation is not uniform across India, with certain states contributing disproportionately to the national total. Maharashtra alone generates nearly 14% of India's total waste, followed closely by Uttar Pradesh and Tamil Nadu. In fact, just six states - Maharashtra, Uttar Pradesh, Tamil Nadu, West Bengal, Karnataka, and Delhi - account for over 53% of the country's waste. Waste generation is an unavoidable consequence of urbanization and economic growth, and understanding per capita waste generation helps in planning effective waste management strategies. On average, an individual in India generates approximately 123.45 grams of waste per day. However, this figure varies significantly across states and union territories. The highest per capita waste generators are Delhi (526.5 g/capita/day), Chandigarh (441.5 g/capita/day), Mizoram (304.3 g/capita/day), and Nagaland (299.1 g/capita/day). In contrast, states with the lowest per capita waste generation include Meghalaya (21.0 g/capita/day), Bihar (39.6 g/capita/day), Assam (44.8 g/capita/day), and Odisha (45.6 g/capita/day). Over the last five years, India has witnessed a steady rise in per capita waste generation, increasing from 98.79 grams per day to 123.45 grams per day. This growing trend highlights the pressing need for improved waste management practices to ensure sustainability.

Out of the total waste generated, 1,56,449 TPD is collected, reflecting an overall collection efficiency of approximately 92%. While this is a positive indication of the country's ability to gather waste, the real challenge lies in what happens next - how much of this waste is effectively processed, treated, and disposed of in an environmentally sound manner.

One of the key aspects of municipal solid waste management is its safe disposal. Sanitary landfilling is considered the final step in solid waste management, meant for the safe disposal of residual and inert waste. These landfills are designed with protective measures to prevent groundwater contamination, air pollution, and the spread of disease. According to the CPCB report 2021-2022, 41,455 TPD, which is 24% of India's waste, is disposed of in sanitary landfills. However, the extent of landfill usage varies across states. Chandigarh (90%), Puducherry (85%), and Sikkim (73%) have the highest proportion of waste being disposed of in landfills, whereas Lakshadweep (0%), Madhya Pradesh (1%), and Chhattisgarh (1.6%) have the lowest. Encouragingly, there has been a decline in the percentage of waste being landfilled, dropping from 54.16% in 2017-2018 to 24% in 2021-2022. Furthermore, 1,244 sites have been identified for use as sanitary landfills, with 669 already constructed and 135 under construction. At present, 645 sanitary landfills are operational, while 10 have reached full capacity and been exhausted.

Open dumping - a practice that is neither environmentally sustainable nor legally recognized under the municipal Solid Waste Management Rules - still occurs in various parts of the country, although its exact extent is not officially recorded. However, due to the lack of sufficient scientifically designed landfills, a significant portion of waste still ends up in dumpsites. India has 2,452 dumpsites, of which 366 have been reclaimed, and 27 have been converted into sanitary landfills.

A circular economy aims to minimize waste and make the most of resources by encouraging reuse, recycling, and energy recovery. The SWM Rules define processing as a scientific method of handling segregated solid waste for reuse, recycling, or conversion into new products. This includes activities such as segregation, sorting, washing, baling, and compaction. On the other hand, treatment involves processes that modify the waste's physical, chemical, or biological characteristics to reduce its volume and environmental impact. This encompasses techniques like composting, vermicomposting, anaerobic digestion for biodegradable waste and incineration, and waste-to-energy (WtE) conversion for MSW.

India employs a mix of waste processing and treatment technologies, including windrow composting, biogasification, organic waste convertors, refuse-derived fuel (RDF) palletization, MRFs, and WtE plants. Organic waste, which makes up a large portion of municipal solid waste, can be composted to produce nutrient-rich manure. Techniques such as windrow composting, vermicomposting, and pit composting allow biodegradable waste to be recycled back into the ecosystem, improving soil health and reducing the need for chemical fertilizers. Cities and municipalities are increasingly adopting decentralized composting facilities to manage organic waste efficiently. Windrow composting is the most widely used method, involving the piling of biodegradable waste into long rows for natural decomposition. Vermicomposting, though smaller in scale, utilizes earthworms to break down organic matter into nutrient-dense compost. Pit composting and Organic Waste Converters (OWC) have been adopted by local bodies in Himachal Pradesh for decentralized organic waste treatment. Biogas plants, such as those in Goa, process all organic waste into methane-rich biogas, which can be used for cooking and electricity generation, reducing reliance on fossil fuels. Composting not only diverts waste from landfills but also reduces methane emissions, a potent greenhouse gas, thus supporting climate action initiatives.

To tackle the challenge of waste disposal and promote sustainable solutions, India has also invested in waste-to-energy (WtE) plants, which convert waste into electricity. Waste-to-energy plants help convert non-recyclable waste into electricity through processes like incineration, pyrolysis, and gasification. These plants significantly reduce the volume of waste that ends up in landfills while generating renewable energy. Currently, there are thirteen operational waste-to-energy plants across the country, located in Andhra Pradesh (2), Delhi (2), Goa (1), Haryana (1), Madhya Pradesh (1), Maharashtra (1), Telangana (1), Uttar Pradesh (3), and West Bengal (1). These plants collectively generate approximately 127.072 MW of power (excluding the unit in Uttar Pradesh), contributing to India's renewable energy goals while reducing landfill dependency.

While significant strides have been taken, only 91,511 TPD (54%) of the total waste generated undergoes some form of processing or treatment. This means that almost half of India's waste still remains untreated, leading to potential environmental and health hazards. However, India has made significant strides in waste processing and treatment. In 2017-2018, only 36.46% of the total waste generated was processed or treated, whereas by 2021-2022, this figure had risen to 54%. This indicates a growing awareness and implementation of sustainable waste management strategies across the nation. Despite efforts in collection, treatment, and disposal, a significant portion of India's waste remains unaccounted for. The difference between the total waste generated and the waste processed or landfilled amounts to 37,373 TPD, which is 22% of the total waste produced. This gap highlights inefficiencies in waste segregation, inadequate processing facilities, and insufficient landfill space.

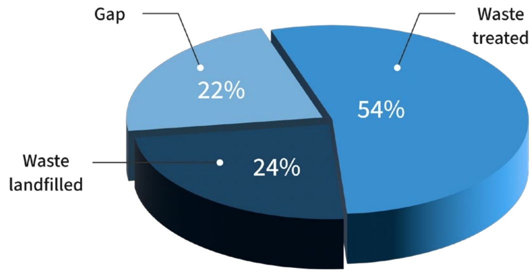


Figure 3: Waste Management Statistics in India for 2021-22

Recommendations for decentralized waste management

Decentralized waste management is a sustainable approach that promotes localized waste processing, reducing dependency on large-scale landfills and centralized facilities. By treating waste at or near the source, this approach minimizes transportation costs, reduces environmental impact, and encourages community participation.

Below are key recommendations for strengthening decentralized waste management in India:

1. Strengthen Source Segregation and Community Participation

- Mandate waste segregation at the household, commercial, and institutional levels into biodegradable, non-biodegradable, and hazardous waste categories.
- Conduct awareness campaigns to educate residents on the importance of segregation and its role in waste reduction.
- Implement reward and penalty systems to encourage compliance among individuals and businesses.

2. Promote Localized Composting for Organic Waste

- Establish community composting centres in residential areas, parks, and marketplaces to process food and garden waste.
- Support home composting initiatives by providing compost bins, training, and incentives for households.
- Partner with farmers and urban gardeners to utilize compost as organic fertilizer, reducing reliance on chemical alternatives.

3. Expand Waste-to-Energy Solutions at Local Levels

- Develop small-scale biogas plants in housing societies, schools, and hotels to convert organic waste into biogas for cooking and electricity.
- Promote the installation of decentralized pyrolysis and gasification units to handle non-recyclable dry waste while generating energy.
- Encourage public-private partnerships to finance and maintain decentralized WtE facilities.

4. Strengthen Recycling Infrastructure for Dry Waste

- Set up MRFs at ward or community levels for efficient sorting and recycling of plastics, paper, glass, and metals.
- Establish collection and buyback centers for recyclables, providing economic incentives for waste pickers and informal recyclers.
- Enforce EPR, ensuring that manufacturers take responsibility for recycling their product packaging.

5. Encourage Zero-Waste Models in Communities and Institutions

- Promote Zero-Waste Cities and Villages, where waste is minimized, and nearly all waste is reused, composted, or recycled.
- Implement green building codes mandating waste management systems in new residential and commercial projects.
- Recognize and incentivize zero-waste institutions, such as schools, offices, and businesses, that implement successful waste reduction models.

6. Integrate Technology for Smart Waste Management

- Deploy IoT-based waste monitoring systems to track waste generation, collection, and processing at decentralized units.
- Develop mobile apps for waste collection requests, composting guides, and locating nearby recycling facilities.
- Use AI-driven waste sorting systems to automate material recovery and reduce contamination.

7. Empower Waste Pickers and Local Entrepreneurs

- Recognize and formalize the role of waste pickers and informal recyclers by integrating them into decentralized waste systems.
- Provide skill training, protective gear, and financial support to improve their working conditions and earnings.
- Support waste-based enterprises like eco-brick making, upcycling units, and plastic recycling start-ups.

8. Reduce Reliance on Landfills and Open Dumping

- Enforce strict regulations against illegal dumping and promote decentralized alternatives.
- Reclaim and convert old dumpsites into parks, green spaces, or solar farms.

Decentralized waste management offers a sustainable and cost-effective solution to India's growing waste crisis. By integrating community-led initiatives, technological innovations, and policy support, waste can be effectively managed at the local level, reducing pollution and enhancing resource efficiency. Implementing these recommendations will accelerate India's transition toward a circular economy and zero-waste future.

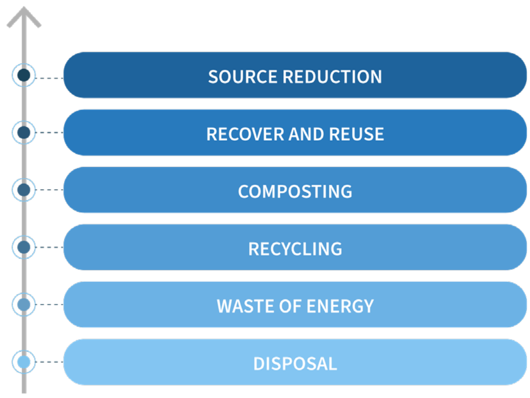


Figure 4: Recommendations for decentralized waste management

Key Enablers for Circular Economy in MSW

- Policy and Governance: Authoritative pressure and policy transformation are pivotal enablers. Governmental bodies can enforce regulations and allocate budgets to support CE initiatives (Pati & Agrawal, 2024).
- Technological Advancements: The adoption of advanced waste treatment methods and infrastructure modernization are essential for efficient waste processing and resource recovery (Sondh et al., 2024).
- Stakeholder Engagement: Engaging various stakeholders, including the informal workforce, is crucial for effective implementation. This includes promoting awareness and aligning interests across sectors (Pati & Agrawal, 2024).

Economic and Environmental Benefits

- **Resource Efficiency:** CE practices can unlock significant economic value, potentially adding half a trillion dollars to India's economy by 2030 (Mandpe et al., 2022).
- **Environmental Impact:** By reducing waste generation and enhancing recycling, CE contributes to environmental sustainability and reduces pollution (Raksha, 2025).

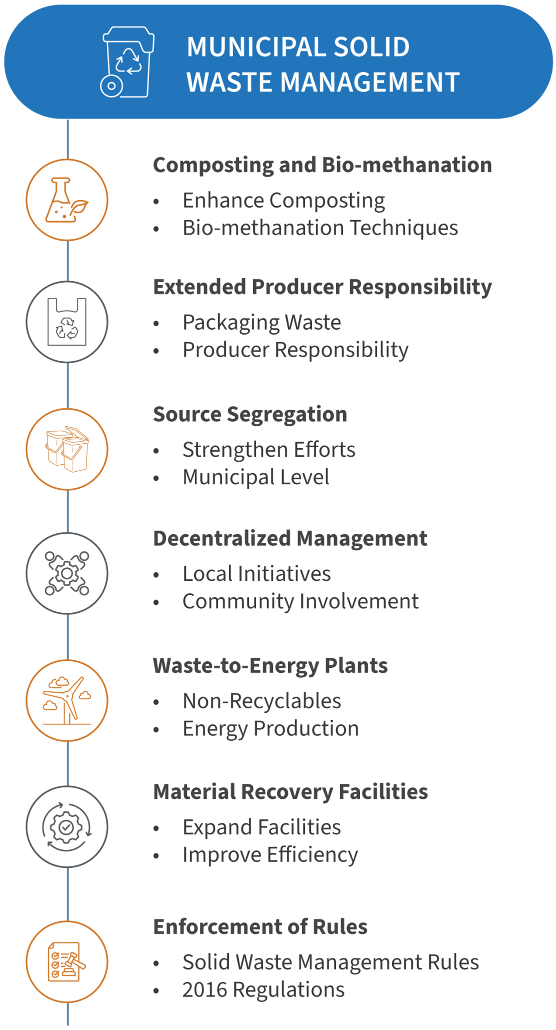


Figure 5: MSW management Strategies

Challenges and Recommendations

A lack of infrastructure and financial resources poses significant challenges. Investment in research and development for cost-efficient systems is necessary. Systematic application of policies and overcoming technological deficits are critical hurdles. Initiatives like the Swachh Bharat Abhiyan and National Resource Efficiency Policy aim to address these issues (Sheth, 2024). While the circular economy offers a promising framework for sustainable MSW management in India, it is not without challenges. The successful implementation of CE requires overcoming financial, technological, and policy-related barriers. Collaborative efforts among government, industry, and communities are essential to realize the full potential of CE in transforming India's waste management landscape.

3.2 Plastic Waste

Current Status & Problem Statement

India generates 3.5 million tons of plastic waste annually, with only 60% collected and a significant portion mismanaged (CPCB, 2021). India has made significant advancements in plastic recycling, with various states implementing innovative strategies to manage plastic waste efficiently. As per the CPCB's 2020-21 report, India has established numerous material collection facilities and resource recovery centers to manage recyclable plastic waste. Clean Kerala Company produced 975 MT of shredded plastic in 2021, and various states have utilized plastic waste for infrastructure development. Plastic waste utilization has also improved, with around 64% of generated plastic waste being processed through different methods, including recycling (81 TPD), road construction (37 TPD), co-processing in cement kilns (70 TPD), refuse-derived fuel (RDF) production (342 TPD), and waste-to-oil conversion (13 TPD). Maharashtra has an 81% collection efficiency, with 55% of waste being recycled or co-processed. Tamil Nadu and Kerala effectively use plastic waste in road construction and co-processing plants, while Delhi has imposed environmental compensation fines for non-compliance with Plastic Waste Management (PWM) rules.

Challenges with Single-Use Plastics (SUPs)

Despite progress, single-use plastics pose significant environmental and regulatory challenges. One of the major issues is regulatory gaps and compliance issues, as many brand owners registered with CPCB fail to report plastic take-back efforts, making it difficult to quantify plastic waste recovery. Several states, including Maharashtra, Tamil Nadu, and Punjab, have imposed a complete ban on single-use plastics, but enforcement and consumer compliance remain barriers.

Another major challenge is the lack of alternative collection and recycling systems. Insufficient waste segregation at the source limits the efficiency of plastic recycling, and many unregistered recyclers and informal sectors handle plastic waste, often under hazardous conditions. Additionally, the transition to sustainable materials is slow due to cost concerns and limited infrastructure for alternative materials.

Alternatives to Plastic and Bio-Based Materials

To transition towards a circular economy, India is exploring several sustainable alternatives. One of these is biodegradable and compostable plastics, with several compostable plastic manufacturing units producing over 10,405 TPA of compostable materials. Puducherry has active compostable plastic manufacturers, such as Poseidon Enterprises (1500 TPA) and Rajaganapathy Bio Polymers (750 TPA). Government guidelines mandate compostable plastics to meet IS 17088:2008 standards.

Another alternative is bio-based and eco-friendly packaging. Bagasse-based packaging (from sugarcane) is emerging as a strong alternative, along with edible cutlery and plates made from millet and wheat bran. Banana leaf packaging and mycelium-based bioplastics are also gaining attention in sustainable markets.

Recycling and reuse models are also being encouraged. Many states are promoting deposit refund systems for plastic bottle returns, and reverse vending machines have been installed in cities like Ranchi and Jamshedpur to collect plastic bottles for recycling. Additionally, co-processing in cement kilns is being widely used to handle non-recyclable plastics efficiently. Also, innovative research and its practicalities are being conducted in polyurethane & waste plastic upcycling.

India's approach to plastic waste management is evolving rapidly, with a strong focus on recycling, bans on SUPs, and the promotion of sustainable alternatives. However, enforcement of regulations, technological advancements in recycling, and consumer awareness are crucial to accelerating India's transition towards a circular economy. By integrating bio-based materials, robust collection systems, and EPR frameworks, India can achieve a sustainable plastic waste management system, ensure minimal environmental impact, and foster economic opportunities.

Roadmap & Recommendations

The problem of plastic waste management has been addressed by CSIR-NEERI in collaboration with CSIRO, Australia, in its National Circular Economy Roadmap for Plastics in India (Dhodapkar et al., 2023). The roadmap discusses seven elements of the circular economy for plastic management in India. The framework entails a clear flow of materials through three broad stages, supported by four primary enablers. In a circular economy, all these elements would be developing at once, each supporting the others as a true system. The inner material flow elements represent what happens to the plastic itself. Products that use plastic would be designed to be recycled. Their manufacture would incorporate recycled 'secondary source' stock rather than virgin material. Any waste from that manufacture would be continually collected and reprocessed, ready for a later manufacturing run.

Given a choice, homes and businesses that consume plastic products would choose those from the circular economy over any linear economy alternative. In their use and re-use of the product and its ultimate disposal, they would be conscious of the need to extend the life of its raw material. At end of life, the item becomes part of the recycling stream, being collected, sorted and processed, ready to become part of its next manufacturing.

None of this physical flow can happen, however, without the four sets of enablers, and it is here that the Roadmap for India's circular economy of plastics would focus. Any business or physical asset needed for production and recycling must be commercially viable, able to attract capital and government incentives to operate in a sustainable market.

Those businesses must operate with the support of digital, research, and planning infrastructure that enables them to become part of a circular system, without having to invent one. Any business owner or plastics user must be engaged on the issues, with the information and, where appropriate, the training available to them. And so that their efforts have the impact they seek, the plastic materials and their treatments must be subject to consistent compliance with appropriate standards, monitoring, and enforcement. The seven elements of the CE in PWM are discussed as follows:

1. Collaborative production: Consider all aspects of the value chain. Substitute virgin plastics with recycled and alternative materials. Design to minimize material, avoid low-value and hard-to-abate plastics, and aid end-of-life decomposition. Design for recyclability by reducing multi-material composites, where possible. Avoid unnecessary plastic packaging. Manufacture efficiently, capturing all waste streams for reuse or recycling. One new idea for production includes bioplastic production from lipid-rich wastewater, which is currently being studied for a more in-depth understanding and for potential application.

2. Sustainable consumption: Choose products with minimal plastics and reject unnecessary plastic packaging. Reuse wherever possible; materials that are kept in circulation are valuable twice over as they reduce the need for virgin materials and reduce waste going to landfill. Reduce plastic consumption and introduce policy, programs, and initiatives that support and enable the avoidance of single-use and low-value plastics. Choose products that are recyclable and made with recycled content. Reject SUP packaging and switch to reusable materials. Reuse wherever possible and provide financial and technology support for business models that encourage sharing and second-hand markets. Dispose responsibly. Segregate into different types of waste streams after use and expand collection systems of all kinds. Work with the informal sector for the efficient collection of waste materials.

3. Effective recycling: Radically improve India's recycling capability, with government-finance-research-industry collaboration. Build sorting facilities with artificial intelligence (AI) capabilities and advanced mechanical and chemical processing infrastructure in proximity to the source for efficient recycling. Push for reverse logistics and state-of-the-art recycling technology to sit alongside industry and commerce in a distributed model, with smaller-scale community-based solutions.

4. Commercial viability: Draw on government and CSR funds both for startups and for those at next-stage commercialization who find it hard to attract capital on manageable terms. Use incentives to prefer circular economy businesses. Develop markets for high-quality secondary material, with government agencies and sustainable corporations seizing the opportunity to 'buy recycled'.

5. Awareness and readiness: For a true 'zero waste' culture, practices must change in industry, in offices, and at home. The channel of schools, universities, and other educational institutions should be used to raise awareness and build readiness and selective curricula on waste management that can be included as a part of the study curriculum. Similarly, waste management policies in industry, administrative, and commercial establishments could drive practices at work and industry premises. That readiness includes the desire to change practices, and ultimately support for the infrastructure and materials needed. Broad national principles should be interpreted into India's multiplicity of communities and languages, with a focus on simple tools that are available on phones and devices, digital information portals, and multi-layered training.

6. Supportive infrastructure: The circular economy would ideally be built on a digital, research and physical backbone. Digital data flows would link material flow from virgin plastics manufacture through to reuse, secondary processing, or disposal. The physical hubs for this data should be local industrial ecologies where manufacturing, materials collection and reprocessing feed each other.

7. Consistent compliance: With a shared national framework and standards, state governments must set targets and monitor progress on plastics reduction, reuse and recycling. After enough time to licence and educate participants in the circular economy, incentive-based enforcement can be pursued to ensure targets are met, and that sustainable companies are not placed at an unfair disadvantage.

- Enforce EPR guidelines for plastics, including producer take-back systems (MoEFCC, 2022).
- Scale up alternatives to single-use plastics and promote bio-based packaging.
- Establish advanced recycling and pyrolysis plants for non-recyclable plastics.
- Integrate informal waste pickers into the formal recycling chain.
- The participants sharing responsibility to make efficient and effective CE in India consists of – Government, industry, informal sector, civil society and community organizations, and households and small businesses.

Figure 6: Strategies for Managing Plastic Waste

3.3 E-Waste

Current Status & Problem Statement

India is the third-largest producer of electronic waste (e-waste) globally, generating approximately **1.6 million tons annually** (CPCB, 2021). However, only **10% of this e-waste is formally recycled**, with the vast majority processed by the informal sector or improperly disposed of in landfills and incinerators. This low recycling rate contributes to severe environmental, health, and economic challenges. E-waste contains hazardous substances such as lead, mercury, and cadmium, which contaminate soil and water, posing risks to ecosystems and human health. Simultaneously, valuable materials like gold, silver, and rare earth metals are lost due to inefficient recovery processes. The lack of robust infrastructure, limited public awareness, and inadequate regulatory enforcement exacerbate the crisis, making sustainable e-waste management a pressing priority for India.

Challenges

1. Dominance of the Informal Sector: Over 90% of e-waste is handled by informal recyclers using unsafe methods like open burning and acid leaching, leading to health risks for workers and environmental pollution.

2. Ineffective Regulatory Framework: The E-Waste (Management) Rules, 2016, lack consistent enforcement, with low compliance among producers and recyclers. The main causes include low flow of e-waste to recyclers due to improper segregation of waste.

3. Low Public Awareness: Limited consumer knowledge about proper e-waste disposal results in low collection rates for formal recycling systems.

4. High-Value Content Loss: Inefficient recycling processes fail to recover valuable materials, leading to significant economic losses and environmental harm.

5. Infrastructure Gaps: A lack of formal recycling facilities and collection systems limits scalable e-waste management.

6. Global E-Waste Trade: Illegal transboundary movement of e-waste from developed to emerging economies like India complicates regulatory oversight and increases environmental risks.

Alternatives

1. Formalizing the Informal Sector: Train and certify informal workers, integrating them into formal recycling systems with access to safer technologies, preserving livelihoods while improving safety. As mentioned in NAMASTE programme, the inclusion of sanitation worker will strengthen UBL to adopt safe and modern sanitation practices. (NAMASTE, 2023)

2. Extended Producer Responsibility Enhancement: Strengthen EPR frameworks to ensure manufacturers are accountable for product lifecycle management, including take-back programs and eco-friendly designs.

3. Public-Private Partnerships: Collaborate with manufacturers, retailers, and tech companies to develop innovative recycling technologies and collection networks.

4. Circular Economy Models: Promote product designs that prioritize repair, refurbishment, and recyclability to reduce e-waste generation.

5. Consumer Awareness Campaigns: Educate the public on proper e-waste disposal through media, schools, and community programs to increase collection rates.

6. Advanced Recycling Technologies: Invest in environmentally friendly recycling facilities to efficiently recover valuable materials. For example, enhanced extraction of critical minerals from E-waste by improving bioavailability.

7. Metal Recovery Techniques: Ongoing research and innovation in recovering metals from PV cells, spent Li batteries will open a new domain for further development.

E-Waste: Challenges vs. Alternatives

Characteristic	Challenges	Alternatives
Informal Sector	Dominance leads to health and environmental risks	Formalizing improves safety and preserves jobs
Regulatory Framework	Inconsistent enforcement and low compliance	EPR ensures manufacturer accountability
Public Awareness	Limited knowledge results in low collection	Campaigns increase collection rates via education
Value Content Loss	Inefficient processes cause economic and environmental harm	Advanced technologies efficiently recover materials
Infrastructure	Lack of facilities limits scalable management	PPPs develop innovative recycling technologies
Global Trade	Illegal movement complicates oversight and increases risks	Circular models prioritize repair and recyclability

Table 1: Challenges and Alternatives of the E-Waste Crisis

Roadmap with Recommendations

To address India's e-waste crisis, a multi-stakeholder, multi-phase roadmap is proposed, integrating regulatory reforms, private sector engagement, informal sector formalization, and public participation. The roadmap is structured into short-term (1–2 years), medium-term (3–5 years), and long-term (5–10 years) phases, with detailed recommendations to ensure scalability, sustainability, and inclusivity.

Short-Term (1–2 Years): Building Foundations

1. Strengthen EPR Implementation

- **Action**: Enforce compliance with the E-Waste (Management) Rules, 2016, through regular audits of producers and recyclers. Introduce stricter penalties for non-compliance and mandate transparent reporting on e-waste collection and recycling.

- **Details**: Establish a national EPR monitoring body to oversee producer compliance, ensuring manufacturers set up accessible take-back systems (e.g., drop-off points at retail stores). Provide incentives like tax credits for companies exceeding recycling targets.
- **Impact**: Increases accountability, boosts formal collection rates, and ensures hazardous materials are processed safely.

2. Pilot Informal Sector Formalization Programs

- **Action**: Launch pilot projects in high e-waste generating cities (e.g., Delhi, Mumbai, Bangalore) to train informal workers in safe recycling practices. Provide access to protective equipment, modern tools, and certifications.
- **Details**: Partner with NGOs and industry bodies to create training modules focusing on health, safety, and efficient material recovery. Subsidize equipment costs for informal workers transitioning to formal systems. Establish micro-enterprises or cooperatives to integrate these workers into the formal economy.
- **Impact**: Improves worker safety, reduces environmental pollution, and preserves livelihoods while transitioning to formal recycling.

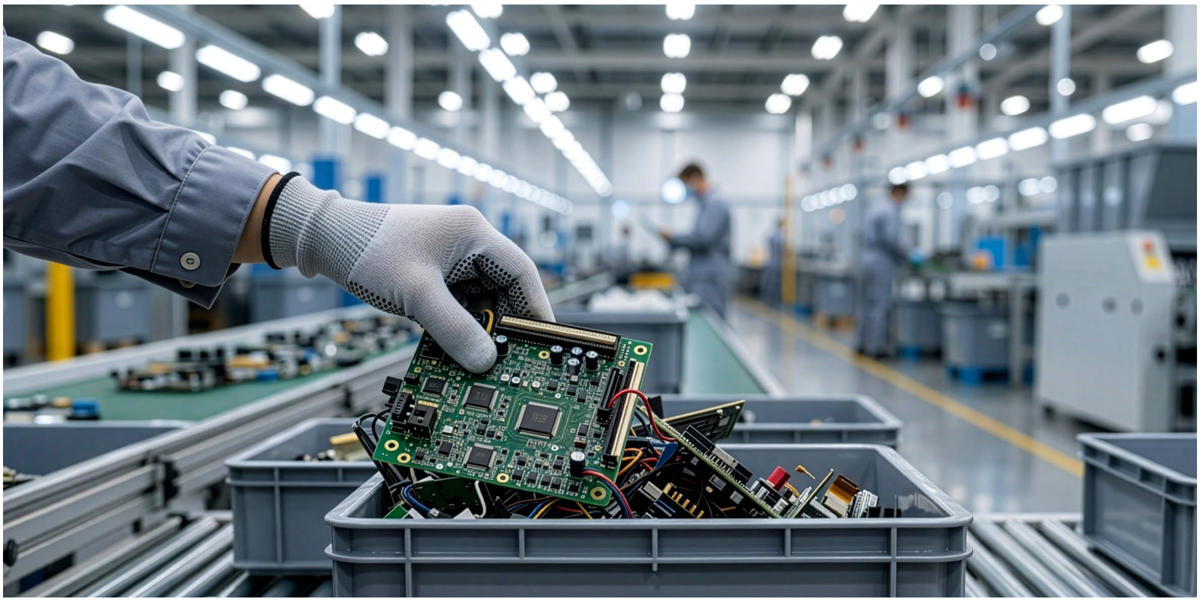
3. Launch Nationwide Awareness Campaigns

- **Action**: Initiate public education campaigns using digital platforms, schools, and local government networks to promote proper e-waste disposal.
- **Details**: Develop engaging content (e.g., videos, infographics) highlighting the environmental and health risks of improper disposal and the benefits of recycling. Collaborate with influencers, schools, and community leaders to reach diverse audiences. Set up e-waste collection drives during festivals or community events. Effective utilization of CSR funds for community development can drive inclusive and sustainable growth.
- **Impact**: Increases consumer participation in formal recycling, reducing illegal dumping and boosting collection rates.

Medium-Term (3–5 Years): Scaling Infrastructure and Innovation

1. Incentivize Private Sector Innovation

- **Action**: Offer financial incentives (e.g., tax breaks, grants) to manufacturers, startups, and tech companies developing sustainable e-waste solutions.
- **Details**: Support R&D for modular electronics, biodegradable components, and advanced recycling technologies (e.g., hydrometallurgical processes for material recovery). Create innovation hubs or incubators focused on e-waste solutions, involving collaboration between universities, tech firms, and recyclers. Encourage retailers to integrate e-waste collection into their supply chains.



- **Impact**: Drives technological advancements, reduces e-waste generation, and creates economic opportunities in the recycling sector.

2. Expand Collection Infrastructure

- **Action**: Develop a nationwide network of e-waste collection centres, leveraging public-private partnerships.
- **Details**: Partner with municipalities and retailers to establish drop-off points in urban and rural areas, ensuring accessibility. Use mobile collection units to reach remote regions. Integrate collection systems with existing waste management frameworks, such as Swachh Bharat Mission, to streamline operations. Provide incentives (e.g., discounts on new electronics) for consumers returning e-waste.
- **Impact**: Increases formal collection rates, reduces reliance on the informal sector, and ensures equitable access to recycling services.

3. Scale Informal Sector Integration

- **Action**: Expand formalization programs nationwide, creating structured pathways for informal workers to join the formal recycling ecosystem.
- **Details**: Establish regional cooperatives for informal workers, providing access to formal recycling facilities, health insurance, and fair wages. Develop a certification framework to recognize skilled workers, ensuring job security. Create public-private partnerships to fund infrastructure for these cooperatives.
- **Impact**: Enhances worker livelihoods, reduces environmental harm, and strengthens the formal recycling ecosystem.

Long-Term (5–10 Years): Systemic Transformation

1. Promote Circular Economy Practices

- **Action**: Encourage manufacturers to adopt circular design principles, prioritizing repairability, refurbishment, and recyclability.
- **Details**: Introduce regulations mandating modular designs (e.g., easily replaceable batteries) and eco-friendly materials. Support refurbishment markets by providing tax incentives for second-hand electronics. Collaborate with global tech companies to adopt circular economy standards tailored to India's context.
- **Impact**: Reduces e-waste generation, extends product lifespans, and maximizes resource recovery.

2. Build Advanced Recycling Facilities

- **Action**: Invest in state-of-the-art recycling plants capable of recovering high-value materials with minimal environmental impact.
- **Details**: Partner with international recycling firms to transfer technology and expertise. Focus on facilities that use green technologies (e.g., automated sorting, non-toxic extraction methods). Ensure facilities are strategically located near high e-waste generation zones to reduce transportation emissions.
- **Impact**: Maximizes material recovery, reduces environmental pollution, and creates jobs in the formal recycling sector.

3. Strengthen Global Cooperation

- **Action**: Collaborate with international organizations to curb illegal e-waste imports and align India's policies with global standards.
- **Details**: Strengthen compliance with the Basel Convention to regulate transboundary e-waste movement. Participate in global forums to share best practices and access funding for e-waste management. Develop bilateral agreements with developed nations to ensure responsible e-waste trade.
- **Impact**: Reduces illegal e-waste inflows, enhances India's global reputation, and supports sustainable practices.

Key Recommendation: Private Sector Engagement

Top-down regulatory approaches alone are insufficient for managing e-waste, given its high-value content and the prevalence of inefficient, unsafe recycling in emerging economies like India. Engaging the private sector - manufacturers, retailers, and labor investors - is critical to drive innovation and scalability. Manufacturers can lead by designing sustainable products and funding recycling initiatives. Retailers can facilitate collection through take-back programs and consumer incentives. Labor investors can support the formalization of informal workers by funding training and infrastructure. By fostering public-private partnerships, India can create a robust, inclusive e-waste management ecosystem that balances environmental protection, economic benefits, and social equity.India's e-waste crisis demands a coordinated, multi-faceted approach

Figure 7: Road Map of E-waste Crisis

to mitigate environmental and health risks while harnessing the economic potential of valuable materials. The e-waste management should protect environmental quality and human health, while employing workers whose source of livelihood depend on the flow of discarded e-waste Awasthi et al., (2019) propose a strategy to encompass e-waste management into a global circular economy (CE) agenda: integrating technical innovation for e-waste processing and financial incentives through multi-agency collaboration to improve rudimentary e-waste management in regions where the waste piles up while labourers and environmental quality are adversely impacted by the toxic components of electronic products.

By strengthening regulations, engaging the private sector, formalizing the informal sector, and raising public awareness, India can build a sustainable e-waste management system. This roadmap provides a clear path toward systemic change, positioning India as a leader in responsible e-waste management among emerging economies.

3.4 Construction and Demolition (C&D) Waste

Current Status & Problem Statement

India generates approximately **150 million tonnes of Construction and Demolition (C&D) waste annually**, yet less than **1% is recycled** (CPCB, 2021). This massive volume of waste, comprising concrete, bricks, wood, metals, and other materials, is largely dumped in landfills, open spaces, or water bodies, leading to environmental degradation, air and water pollution, and loss of valuable resources. The lack of systematic collection, segregation, and recycling infrastructure, coupled with limited regulatory enforcement and low awareness, exacerbates the problem. Improper C&D waste management contributes to urban flooding, soil contamination, and missed economic opportunities from recyclable materials, making sustainable C&D waste management a critical priority for India's urban development.

Challenges

1. Low Recycling Rates: With less than 1% of C&D waste recycled, the majority is disposed of unsustainably, leading to environmental and resource losses.

2. Lack of Segregation: Most C&D waste is not segregated at the source, complicating recycling efforts and increasing processing costs.

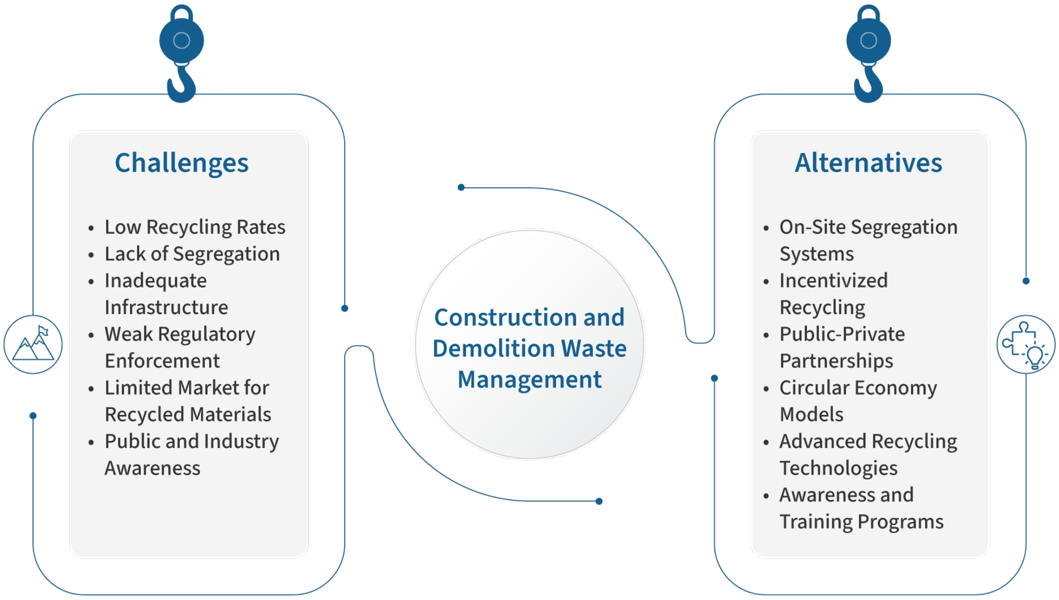


Figure 8: Challenges and Alternatives of C& D waste Management

3. Inadequate Infrastructure: Limited dedicated C&D waste recycling facilities and collection systems hinder scalable waste management.

4. Weak Regulatory Enforcement: The C&D Waste Management Rules, 2016, lack consistent implementation, with low compliance among construction firms and local bodies.

5. Limited Market for Recycled Materials: Low demand for recycled C&D products due to quality concerns, lack of standards, and preference for virgin materials.

6. Public and Industry Awareness: Insufficient awareness among stakeholders about the benefits of C&D waste recycling and proper disposal practices.

Alternatives

1. On-Site Segregation Systems: Implement mandatory segregation of C&D waste at construction sites to facilitate recycling and reduce contamination.

2. Incentivized Recycling: Offer financial incentives, such as support and affiliate them with carbon credits and recognition to these construction firms using recycled C&D materials.

3. Public-Private Partnerships: Collaborate with private sector players to establish recycling plants and develop markets for recycled products.

4. Circular Economy Models: Promote the use of recycled aggregates and materials in construction and infrastructure projects to reduce reliance on virgin resources.

5. Advanced Recycling Technologies: Invest in modern recycling facilities capable of processing diverse C&D waste streams into high-quality materials.

6. Awareness and Training Programs: Educate contractors, developers, and local bodies on sustainable C&D waste management practices.

7. Enhanced Recovery Techniques: Ongoing research and innovation in converting stone waste to building materials or the development of flooring tiles from Fluorogypsum will prove to be significant in the future.

Roadmap with Recommendations

To address India's C&D waste crisis, a phased, multi-stakeholder roadmap is proposed, integrating regulatory reforms, infrastructure development, private sector engagement, and public awareness. The roadmap builds on the provided recommendations - mandatory on-site segregation, incentivizing recycled material use, developing recycling plants, and promoting recycled aggregates - while elaborating with actionable strategies to ensure scalability and sustainability.

Short-Term (1–2 Years): Establishing Foundations

1. Mandate On-Site Segregation

- **Action**: Enforce mandatory segregation of C&D waste at construction and demolition sites, as outlined in the C&D Waste Management Rules, 2016.
- **Details**: Require construction firms to segregate waste into categories (e.g., concrete, metals, wood, plastics) using labeled bins or zones. Local urban bodies should monitor compliance through site inspections and impose fines for non-compliance. Develop standardized guidelines for segregation, tailored to small and large projects.
- **Impact**: Improves recyclability of materials, reduces contamination, and lowers processing costs at recycling facilities.

2. Incentivize Use of Recycled Materials

- **Action**: Introduce financial incentives to encourage the use of recycled C&D materials in construction projects (MoHUA, 2022).
- **Details**: Offer tax rebates, subsidies, or low-interest loans to developers and contractors using recycled aggregates or products (e.g., recycled concrete blocks). Create certification programs to ensure the quality of recycled materials meets industry standards, addressing concerns about reliability. Partner with industry associations to promote adoption.
- **Impact**: Boosts demand for recycled products, reduces reliance on virgin materials, and supports a circular economy.

3. Launch Awareness and Training Programs

- **Action**: Initiate nationwide campaigns to educate stakeholders on C&D waste management and recycling benefits.
- **Details**: Target contractors, developers, architects, and municipal officials through workshops, online training modules, and certification programs. Use media campaigns (e.g., social media, radio, billboards) to inform the public about proper C&D waste disposal and recycling options. Integrate C&D waste management into urban planning curricula.
- **Impact**: Increases stakeholder buy-in, improves compliance, and fosters a culture of sustainable waste management.

Medium-Term (3–5 Years): Scaling Infrastructure and Adoption

1. Develop C&D Recycling Plants in Major Cities

- **Action**: Establish dedicated C&D waste recycling facilities in all major cities to process waste locally and reduce transportation costs.
- **Details**: Identify high C&D waste-generating cities (e.g., Delhi, Mumbai, Bangalore, Chennai) and set up recycling plants through public-private partnerships. Equip facilities with modern technologies like automated sorting, crushing, and screening to produce high-quality recycled aggregates. Subsidize initial setup costs and provide land allocation support from local governments.
- **Impact**: Enhances recycling capacity, reduces illegal dumping, and creates jobs in the recycling sector.

2. Promote Recycled Aggregates in Infrastructure Projects

- **Action**: Mandate the use of recycled C&D aggregates in public infrastructure projects, such as roads, bridges, and public buildings.
- **Details**: Amend procurement policies to prioritize recycled materials in government-funded projects (e.g., Smart Cities Mission, AMRUT). Develop standards and testing protocols for recycled aggregates to ensure quality and safety. Partner with road construction agencies to pilot projects using recycled materials, showcasing their viability. Provide incentives for private infrastructure projects adopting recycled products.
- **Impact**: Creates a stable market for recycled materials, reduces environmental impact, and conserves natural resources.

3. Strengthen Regulatory Enforcement

- **Action**: Enhance enforcement of the C&D Waste Management Rules through a dedicated monitoring framework.
- **Details**: Establish state-level task forces to oversee compliance, conduct regular audits of construction sites, and penalize illegal dumping. Integrate C&D waste management into urban local body mandates, ensuring accountability. Develop a digital platform to track waste generation, collection, and recycling across cities.

- **Impact**: Improves regulatory compliance, reduces environmental pollution, and streamlines waste management processes.

Long-Term (5–10 Years): Systemic Transformation

1. Promote Circular Economy Practices

- **Action**: Encourage construction firms to adopt circular design principles, such as modular construction and reusable materials.
- **Details**: Introduce regulations mandating the use of recyclable or reusable materials in new construction projects. Support research and development for innovative materials (e.g., low-carbon concrete, recyclable composites). Establish a national marketplace for refurbished construction materials to promote reuse. Provide tax incentives for developers adopting circular practices.
- **Impact**: Reduces C&D waste generation, extends material lifespans, and minimizes resource extraction.

2. Expand National Recycling Infrastructure

- **Action**: Scale up C&D waste recycling facilities to cover semi-urban and rural areas, creating a nationwide network.
- **Details**: Use successful urban recycling models to replicate facilities in smaller cities and towns. Develop mobile recycling units for remote areas with low waste volumes. Foster public-private partnerships to fund expansion and ensure long-term sustainability. Integrate C&D waste management into national urban development programs like Swachh Bharat Mission.
- **Impact**: Ensures equitable access to recycling infrastructure, reduces illegal dumping, and supports sustainable urban growth.

3. Foster Global and Industry Collaboration

- **Action**: Collaborate with international organizations and industry leaders to adopt global best practices in C&D waste management.
- **Details**: Partner with organizations like the United Nations Environment Programme to access technical expertise and funding. Adopt global standards for recycled C&D materials to enhance market acceptance. Engage with construction industry associations to promote sustainable practices and share innovations. Participate in global forums to showcase India's progress in C&D waste management.
- **Impact**: Enhances India's global standing, attracts investment, and accelerates the adoption of advanced technologies.

Figure 9: Road Map of C &D Waste Management

Key Recommendation: Private Sector and Community Engagement

While regulatory mandates are essential, top-down approaches alone cannot address the scale of India's C&D waste challenge. Engaging the private sector - construction firms, developers, and recycling companies - is critical to drive innovation and infrastructure development. Incentives for using recycled materials, combined with public-private partnerships to build recycling plants, will create a sustainable ecosystem. Additionally, community engagement through awareness campaigns and training programs will ensure stakeholder buy-in, improving segregation and collection rates. By integrating these efforts, India can transform C&D waste into a valuable resource, supporting sustainable urban development and economic growth.

India's C&D waste crisis, with 150 million tonnes generated annually and less than 1% recycled, demands urgent action to mitigate environmental degradation and harness economic potential. By enforcing on-site segregation, incentivizing recycled material use, developing recycling infrastructure, and promoting recycled aggregates, India can build a robust C&D waste management system. This roadmap provides a clear path toward systemic change, positioning India as a leader in sustainable construction waste management among emerging economies.

3.5 Industrial and Hazardous Waste

Current Status and Problem Statement

India, like many rapidly developing nations, faces significant challenges in managing industrial and hazardous waste, driven by its booming industrial sector, rapid urbanization, and population growth. With an estimated **62 million metric tonnes of industrial waste** generated annually, including **7.9 million tonnes of hazardous waste** (CPCB, 2020), the country grapples with environmental and public health risks. The global context, as seen in countries like China and Vietnam, highlights similar issues: inadequate infrastructure, weak regulatory frameworks, and the need for innovative strategies like the **reduce, reuse, and recycle (3R)** approach. This analysis integrates the global perspective with India's unique challenges, providing a detailed examination of the current status, challenges, and a robust roadmap for sustainable waste management. The roadmap incorporates specific recommendations - strengthening compliance monitoring, developing industrial symbiosis programs, and establishing digital tracking systems - while drawing on global best practices, such as those outlined in the Basel Convention and strategies from China and Vietnam.

India's industrial landscape, encompassing sectors like mining, manufacturing, chemicals, pharmaceuticals, and electronics, generates substantial waste. Hazardous waste, including heavy metals, chemical residues, and electronic waste (e-waste), accounts for **7.9 million tonnes annually**, with major contributions from industrial hubs in Maharashtra, Gujarat, Tamil Nadu, and Uttar Pradesh (CPCB, 2020). E-waste alone has surged to **3.2 million tonnes per year**, driven by the proliferation of electronic devices. Despite regulatory frameworks like the **Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016**, India's waste management system is fragmented and plagued by non-compliance, mirroring challenges in countries like China and Vietnam.

- **India's Context**: The CPCB (2021) reports that only **43% of hazardous waste** is treated scientifically, with illegal dumping and informal recycling prevalent, particularly among small and medium enterprises (SMEs). The **48 Common Hazardous Waste Treatment, Storage, and Disposal Facilities (TSDFs)** are insufficient, especially in eastern and northeastern states like Bihar and Assam. The rise in biomedical waste post COVID-19 and e-waste from rapid digitization further strains the system.
- **Global Comparison**: In China, rapid industrial growth has similarly increased hazardous waste, with inadequate treatment facilities and a lack of integrated management plans. Vietnam faces rising quantities and varieties of hazardous waste, compounded by insufficient technical infrastructure and legal frameworks. Like India, both nations struggle with enforcement and infrastructure gaps, but China's investments in advanced treatment technologies and Vietnam's adoption of the 3R concept offer lessons for India.

Key Issues in India

- **Non-Compliance**: Many industries, especially SMEs, bypass regulations due to weak monitoring, leading to environmental contamination. For example, unregulated chemical waste disposal in Vapi, Gujarat, has polluted groundwater.
- **Fragmented System**: Lack of coordination between the CPCB, SPCBs, and industries results in inconsistent standards and enforcement.
- **Inadequate Infrastructure**: The limited number of TSDFs and their uneven distribution leave rural and semi-urban areas reliant on unsafe disposal methods.
- **Emerging Waste Streams**: E-waste and biomedical waste require specialized facilities, which are currently inadequate. Informal recycling of e-waste, using methods like acid leaching, poses health risks.
- **Public Perception**: Similar to global trends, public perception in India often attributes waste generation solely to large corporations, overlooking SMEs' significant contributions.

Challenges

India's industrial and hazardous waste management faces multifaceted challenges, many of which align with global issues observed in countries like China and Vietnam:

- **Inadequate Disposal Facilities**: With only 48 TSDFs, India lacks the capacity to handle its hazardous waste volume. States like Odisha and the Northeast have minimal access, forcing reliance on unregulated disposal, similar to Vietnam's infrastructure deficits. (Quynh, 2020)
- **Weak Regulatory Frameworks and Enforcement**: Despite the Environment Protection Act, 1986, and Hazardous Waste Rules, 2016, enforcement is inconsistent due to bureaucratic inefficiencies, limited trained personnel.
- **Lack of Comprehensive Management Plans**: India lacks integrated waste management strategies, leading to fragmented efforts across states. China's experience highlights the need for cohesive plans to address rising waste volumes (EU, 2024).
- **Public and Industrial Misconceptions**: As noted globally, there is a misconception in India that large corporations are the primary waste generators, ignoring SMEs, which often lack resources for compliance.
- **Urban-Rural Divide**: Urban industrial hubs like Maharashtra and Gujarat have better infrastructure, while rural areas rely on open dumping or burning, polluting air and water sources like the Ganges.
- **Emerging Waste Streams**: The rapid rise in e-waste (3.2 million tonnes annually) and biomedical waste requires specialized facilities, which are scarce. This challenge is akin to Vietnam's struggle with diverse waste types.
- **Economic Barriers**: SMEs view compliance as costly, deterring investment in proper waste management. This is a global issue, as seen in China's need for technical capability improvements (EU, 2024).

Roadmap and Recommendations

To address India's waste management challenges and align with global best practices, a comprehensive roadmap is proposed, integrating the provided recommendations (compliance monitoring, industrial symbiosis, digital tracking) with additional strategies inspired by China, Vietnam, and the Basel Convention. The roadmap emphasizes systemic reform, innovation, and international collaboration to achieve a sustainable, circular economy.

1. Strengthen Compliance Monitoring for Hazardous Waste Treatment Facilities:

- **Strategy**: Deploy a real time compliance monitoring system for TSDFs using IoT sensors and blockchain technology to ensure transparency and traceability. This aligns with China's focus on improving technical capabilities.
- **Implementation**: The CPCB and SPCBs should pilot this system in high-waste-generating states (Maharashtra, Gujarat, and Tamil Nadu) by 2026, with nationwide adoption by 2028. Train officials in advanced auditing, drawing from the EU's **Waste Framework Directive**. Increase inspections to quarterly for high-risk sectors like chemicals.
- **Impact**: Gujarat's real time TSDF monitoring reduced violations by **20%** (CPCB, 2020), and scaling this could curb illegal dumping. China's investment in monitoring technologies offers a model for India.
- **Global Context**: China's emphasis on strengthening hazardous waste source management supports India's need for robust enforcement.

2. Develop Industrial Symbiosis Programs to Reuse Waste By-Products:

- **Strategy**: Promote industrial symbiosis, where waste from one industry (e.g., fly ash, slag) is reused in another (e.g., cement, construction). This aligns with Vietnam's **3R** strategy and India's success with fly ash utilization (80% in 2020, Ministry of Power, 2021).
- **Implementation**: Establish **Industrial Symbiosis Parks** in Vapi, Chennai, and Jamshedpur, modelled after Denmark's Kalundborg Symbiosis. Partner with FICCI and CII to map waste streams and offer tax incentives for participation. Pilot by 2027, scaling to 10 hubs by 2030. (UNIDO, 2017); (EU, 2024)
- **Impact**: Symbiosis reduces landfill dependency, as seen in India's fly ash reuse, and fosters a circular economy. Vietnam's 3R approach demonstrates the viability of waste reuse in developing economies.
- **Global Context**: The global push for 3R strategies supports India's adoption of symbiosis to manage diverse waste streams. (KOJIMA, 2010); (UNCRD, 2009).

3. Establish Digital Tracking Systems for Hazardous Waste Movement and Disposal:

- **Strategy**: Develop a national **Hazardous Waste Tracking System (HWTS)** using GPS, QR codes, and a centralized database, modeled after the EU's **e-Manifest** system. This addresses India's fragmented system and aligns with global calls for transparency.
- **Implementation**: Mandate industries to log waste details, with automated penalties for non-compliance. Pilot in Maharashtra, Gujarat, and Tamil Nadu by 2026, with full integration by 2029. Integrate with CPCB and SPCB databases.
- **Impact**: Tamil Nadu's pilot tracking system reduced non-compliance by **15%** (CPCB, 2021), and nationwide adoption could enhance accountability. The EU's success in reducing illegal waste shipments by **30%** offers a benchmark.
- **Global Context**: The Basel Convention's emphasis on monitoring transboundary waste movements supports India's need for digital tracking.

4. Expand Infrastructure for Hazardous Waste Management:

- **Strategy**: Increase TSDFs to **100 by 2030**, prioritizing underserved regions like Bihar and the Northeast. Promote co-processing in cement kilns, as seen in Gujarat, to reduce landfill use.
- **Implementation**: Leverage public-private partnerships to fund new facilities. Subsidize waste-to-energy technologies. Gujarat's co-processing reduced landfill use by **25%** (CPCB, 2020).
- **Impact**: Expanded infrastructure will address capacity gaps, similar to China's push for more treatment facilities.
- **Timeline**: Develop 20 new TSDFs by 2028, with an additional 32 by 2030.

5. Adopt Advanced Waste Treatment Technologies:

- **Strategy**: Invest in **plasma arc gasification**, **bioremediation**, and **chemical neutralization** for complex waste streams, as recommended globally.
- **Implementation**: Pilot projects in Hyderabad and Bengaluru by 2027, partnering with IITs and funded by the **Swachh Bharat Mission** or international grants.
- **Impact**: Technologies like bioremediation can treat contaminated sites, as seen in Assam's oilfields, reducing environmental risks.
- **Global Context**: China's focus on advanced technologies (Li, 2013) supports India's adoption of innovative solutions.

6. Promote Public and Industrial Awareness:

- **Strategy**: Launch campaigns to educate SMEs and communities, addressing misconceptions about waste sources. Integrate with **Make in India** to promote compliance.
- **Implementation**: Partner with media, NGOs, and industry bodies for workshops and social media campaigns by 2026, with ongoing efforts through 2030.
- **Impact**: Increased awareness will foster voluntary compliance, reducing enforcement burdens.
- **Global Context**: Public perception challenges noted globally highlight the need for awareness in India.

7. Foster International Collaboration:

- **Strategy**: Strengthen adherence to the **Basel Convention** through technology transfers from countries like Germany and Japan. Enhance monitoring of transboundary waste.
- **Implementation**: Establish bilateral agreements by 2026, participating in global forums like the **Conference of the Parties (COP)**.
- **Impact**: Collaboration will enhance technical capabilities, as seen in China's partnerships.
- **Global Context**: The Basel Convention's global standards provide a framework for India to emulate.

8. Address Emerging Waste Streams:

- **Strategy**: Develop dedicated facilities for e-waste and biomedical waste, enforcing **E-Waste (Management) Rules, 2022**, and EPR frameworks.
- **Implementation**: Build 50 new facilities by 2030 through PPPs, focusing on tier-2 and tier-3 cities.
- **Impact**: Formal recycling will reduce health risks from informal practices, addressing Vietnam's similar challenges.

Road Map of Hazardous and Industrial Waste Management

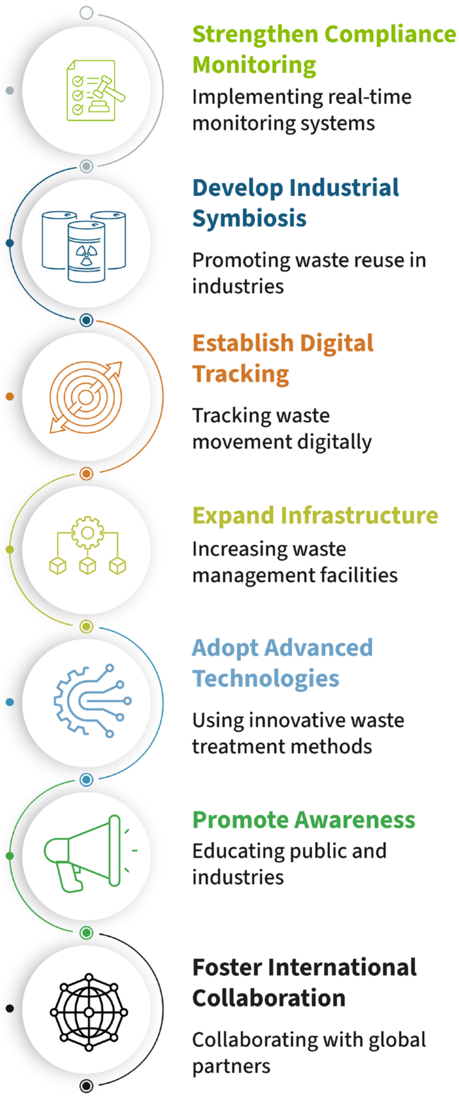


Figure 10: Road Map of Hazardous and Industrial Waste Management

India’s industrial and hazardous waste management system faces significant challenges, including fragmented management, non-compliance, and inadequate infrastructure, which mirror global issues seen in China and Vietnam. The annual generation of 62 million tonnes of industrial waste, including 7.9 million tonnes of hazardous waste, demands urgent action to mitigate environmental and health risks.

The proposed roadmap - strengthening compliance monitoring, developing industrial symbiosis, establishing digital tracking, expanding infrastructure, adopting advanced technologies, promoting awareness, fostering international collaboration, and addressing emerging waste streams - integrates India-specific solutions with global best practices like the 3R concept and Basel Convention standards. Pilot successes in Gujarat and Tamil Nadu demonstrate scalability, and with concerted efforts, India can achieve a sustainable, circular economy by 2030, ensuring a cleaner environment and healthier future.

3.6 Agricultural and Organic Waste

Current Status & Problem Statement

Agricultural and organic waste, encompassing crop residues (e.g., rice straw, wheat stubble), livestock manure, and food processing byproducts, represents a critical environmental and economic challenge worldwide. The Indian Council of Agricultural Research (ICAR) reported that stubble burning, particularly in regions like Punjab and Haryana, significantly contributes to air pollution, releasing pollutants such as particulate matter (PM2.5), carbon monoxide, volatile organic compounds, and greenhouse gases like carbon dioxide and methane. These emissions degrade air quality, cause respiratory health issues, and exacerbate climate change. Globally, mismanagement of agricultural waste leads to soil degradation through nutrient depletion, water contamination from runoff, and missed opportunities for resource recovery (Food and Agriculture Organization, 2017). The lack of scalable, cost-effective, and sustainable waste management systems, compounded by limited awareness and inadequate infrastructure, imposes significant burdens on farmers and rural communities. Addressing these issues requires innovative, inclusive solutions that balance environmental sustainability with economic viability for stakeholders.

Challenges

Implementing sustainable agricultural and organic waste management practices faces several complex barriers:

1. High Capital and Operational Costs: Establishing bio-energy plants, composting facilities, or advanced waste processing units demands substantial upfront investment, often unaffordable for small-scale farmers or rural cooperatives. Ongoing operational costs, including maintenance and labor, further strain limited budgets (Bhuvaneshwari et al., 2019).

2. Limited Awareness and Technical Expertise: Many farmers lack knowledge about sustainable waste management techniques, such as composting, bio-fertilizer production, or residue-based energy generation. The absence of accessible training programs perpetuates reliance on traditional practices like stubble burning.

3. Logistical and Infrastructure Barriers: Collecting and transporting agricultural waste to processing centers is hindered by poor rural transportation networks, inadequate storage facilities, and limited access to processing infrastructure, particularly for small and marginal farmers (Bhuvaneshwari et al., 2019).

4. Policy and Incentive Gaps: Inconsistent or insufficient government policies and subsidies discourage farmers from adopting sustainable practices. The lack of guaranteed markets for bio-fertilizers or bio-energy products reduces economic incentives (Food and Agriculture Organization, 2017).

5. Cultural and Behavioral Resistance: Long-standing practices like stubble burning are deeply ingrained in some farming communities due to their simplicity and low immediate cost, making it challenging to shift to alternatives without significant outreach and support.

6. Market Underdevelopment: The demand for compost and bio-fertilizers is constrained by underdeveloped markets, low consumer awareness, and competition with cheaper

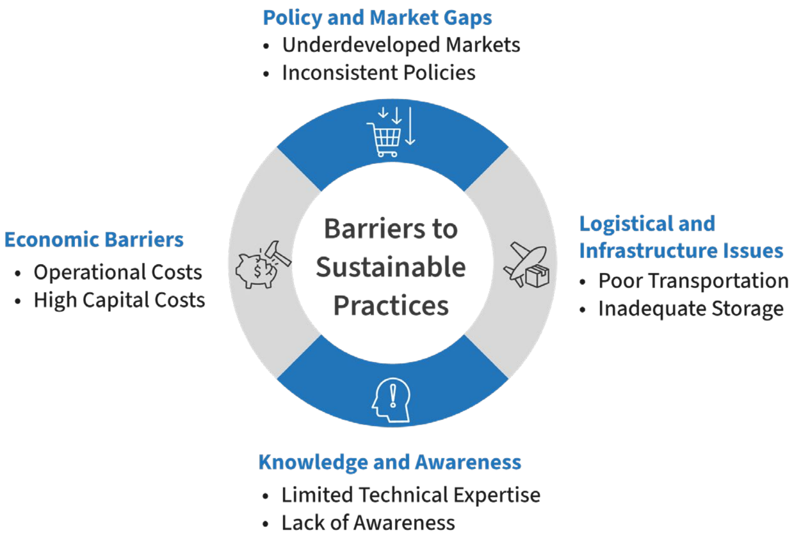


Figure 11: Challenges of Agriculture Waste Management

chemical fertilizers, limiting economic viability for farmers (Food and Agriculture Organization, 2017).

Alternatives

Before outlining a roadmap, several alternative approaches can complement or serve as substitutes for conventional solutions, addressing the identified challenges:

1. In-Situ Crop Residue Management: Practices like mulching or direct incorporation of crop residues into the soil enhance soil fertility, improve water retention, and reduce erosion. Technologies like the Happy Seeder allow farmers to sow crops without clearing residues, reducing stubble burning while maintaining productivity (Indian Council of Agricultural Research, 2021). This approach is cost-effective and requires minimal infrastructure, making it accessible for small farmers.

2. Community-Based Waste Management Models: Local cooperatives can manage waste collection, composting, or bio-energy production, reduce logistical challenges and distribute costs. Village-level composting units have shown success in pilot projects in India, improving waste utilization and fostering community engagement (Maurya et al., 2020).

3. Biomass-Based Non-Energy Products: Crop residues can be repurposed into value-added products like biodegradable packaging, paper, or construction materials (e.g., particle boards). These products diversify income streams and reduce dependence on energy-focused solutions, which may face market or technological barriers (Bhuvaneshwari et al., 2019).

4. Agroforestry Integration: Using crop residues as mulch or fodder in agroforestry systems enhances biodiversity, sequesters carbon, and provides additional revenue through timber or fruit production. This approach aligns with sustainable land use and reduces waste disposal needs (Food and Agriculture Organization, 2017).

5. Mobile Technology and Extension Services: Mobile apps, SMS-based advisories, and strengthened agricultural extension services can provide real time guidance on waste management practices, bridging knowledge gaps. These platforms can also connect farmers to markets for compost or bio-fertilizers, enhancing economic viability (Maurya et al., 2020).

6. Anaerobic Digestion for Small-Scale Farmers: Small-scale biogas digesters convert livestock manure and crop residues into biogas for household energy and digestate for fertilizer. These systems are particularly suitable for remote areas with limited access to large-scale bio-energy plants (Bhuvaneshwari et al., 2019).

7. Post-Harvest Agri-waste Processing: Research and applications are ongoing to convert post-agricultural waste into nutritive cattle fodder by a combination of mechanical and chemical processing.

8. Innovative Approaches: Novel techniques like converting agrowaste and cow dung into bio-based composite material and hydrothermal carbonization of waste biomass will be of much aid in the near future.

Roadmap & Recommendations

To address the challenges and leverage alternative approaches, a comprehensive roadmap for sustainable agricultural and organic waste management is proposed:

1. Promote Bio-Energy Plants Using Crop Residues: Develop and scale bio-energy plants that convert crop residues into renewable energy sources, such as biogas, bioethanol, or electricity. These plants provide a viable alternative to stubble burning, reducing air pollution while generating energy. Decentralized, small-scale bio-energy units can improve accessibility for small and marginal farmers. Public-private partnerships can facilitate technology transfer, infrastructure development, and operational support. Pilot projects in regions like Punjab and Haryana have demonstrated reductions in air pollution and economic benefits for farmers (Indian Council of Agricultural Research, 2021). To address high costs, governments can provide capital subsidies or low-interest loans for plant setup, ensuring affordability and scalability.

2. Scale up Organic Composting and Bio-Fertilizer Production: Expand the adoption of organic composting and bio-fertilizer production to transform agricultural and organic waste into valuable resources. Composting crop residues and livestock manure improves soil health, reduces reliance on chemical fertilizers, and enhances crop yields. Governments and NGOs can support this by establishing training programs, providing subsidized composting equipment (e.g., vermicomposting units), and creating certification systems to ensure product quality. Bio-fertilizers, derived from waste through microbial processes, offer a sustainable alternative to synthetic inputs. Awareness campaigns and market linkages can address market underdevelopment by promoting demand among farmers and consumers (Food and Agriculture Organization, 2017).

3. Provide Financial Incentives for Sustainable Waste Management Practices: Introduce robust financial incentives, such as subsidies for purchasing equipment like balers, shredders, or biogas digesters, and direct benefit transfers for farmers who avoid stubble burning or invest in waste-to-resource technologies. Tax exemptions or low-interest loans can further reduce the financial burden of transitioning to sustainable practices. Public-private partnerships can ensure the availability of affordable technologies and create buy-back schemes for compost or bio-energy products, enhancing economic viability. To address policy gaps, governments should streamline incentive programs and ensure equitable access for small-scale farmers (Bhuvaneshwari et al., 2019). Agricultural and organic waste management is a pressing issue that demands innovative, scalable, and inclusive solutions to mitigate environmental impacts and unlock economic opportunities. Challenges such as high costs, limited awareness, logistical barriers, and market constraints must be addressed through a combination of alternative approaches and targeted recommendations. In-situ residue management, community-based models, biomass-based products, agroforestry, mobile technology, and small-scale anaerobic digestion offer practical pathways to complement the proposed roadmap. By promoting bio-energy plants, scaling up composting and bio-fertilizer production, and providing financial incentives, stakeholders can transform agricultural waste from a pollution source into a valuable resource. These efforts, supported by robust policy frameworks and community engagement, align with circular economy principles and contribute to sustainable development goals, fostering healthier ecosystems and resilient agricultural communities.

3.7 Biomedical Waste

India generates approximately 775 tonnes of biomedical waste (BMW) daily, driven by its expansive healthcare sector (CPCB, 2022). This waste, comprising infectious, hazardous, and non-hazardous materials, poses significant risks to public health, healthcare workers, and the environment due to improper segregation, inadequate treatment infrastructure, and inconsistent regulatory enforcement. The Biomedical Waste Management Rules, 2016, provide a framework, but challenges like limited awareness, insufficient facilities, and weak monitoring persist. This report elaborates on the current status, challenges, alternative solutions, a detailed roadmap with actionable recommendations, and references to enhance BMW management in India.

Current Status & Problem Statement

India's healthcare system, encompassing hospitals, clinics, diagnostic laboratories, and research institutions, produces around 775 tonnes of biomedical waste daily (Central Pollution Control Board, 2022). This includes:

- **Infectious Waste**: Used syringes, bandages, and pathological waste.
- **Hazardous Waste**: Chemical disinfectants, expired drugs, and sharps.
- **Non-Hazardous Waste**: General waste like paper or food scraps from healthcare facilities.

The Biomedical Waste Management Rules, 2016, mandate segregation, treatment, and disposal through authorized Common Biomedical Waste Treatment Facilities (CBWTFs). However, key issues undermine effective management:

- **Improper Segregation**: Many healthcare facilities mix infectious and non-infectious waste at the source, increasing treatment costs and health risks (Sharma et al., 2020).
- **Health and Environmental Risks**: Improper disposal leads to infections among waste handlers (e.g., hepatitis, HIV) and environmental contamination through leachate or air pollution from unregulated incineration (Datta et al., 2018).
- **Regulatory Gaps**: Compliance is inconsistent, especially in rural and small-scale facilities, due to limited oversight and resources (CPCB, 2022).
- **Infrastructure Shortages**: As of 2022, India has only 202 CBWTFs, insufficient for its vast healthcare network, leading to illegal dumping or inadequate treatment (CPCB, 2022).

These challenges highlight the urgent need for systemic improvements to ensure safe and sustainable BMW management.

Challenges in Biomedical Waste Management

1. Inadequate Segregation at Source:

- Many healthcare facilities lack standardized protocols or training, resulting in mixed waste streams.

ROAD MAP FOR AGRICULTURE AND ORGANIC WASTE MANAGEMENT

CHARACTERISTIC	BIO-ENERGY PLANTS	ORGANIC COMPOSTING & BIO-FERTILIZER	FINANCIAL INCENTIVES
GOAL	Renewable energy production	Transform waste into resources	Promote sustainable practices
METHOD	Convert crop residues to energy	Composting and microbial processes	Subsidies, tax exemptions, and loans
BENEFITS	Reduces air pollution, generates energy	Improves soil health, reduces chemical use	Reduces financial burden, ensures access
SUPPORT	Public-private partnerships, subsidies	Training programs, subsidized equipment	Streamlined programs, equitable access

Figure 12: Road Map of Agriculture and Organic Waste Management

- Small clinics and rural hospitals often use single bins, complicating downstream treatment (Sharma et al., 2020).
- Impact: Mixed waste increases the volume requiring specialized treatment, raising costs and risks.

2. Limited Treatment Infrastructure:

- CBWTFs are concentrated in urban areas, leaving rural regions underserved.
- Many facilities rely on outdated incinerators that emit toxic pollutants like dioxins (Datta et al., 2018).
- Impact: Rural facilities resort to open burning or illegal dumping, exacerbating environmental harm.

3. Lack of Awareness and Training:

- Healthcare workers and waste handlers often lack knowledge of BMW categories and handling protocols (Mathur et al., 2019).
- Public awareness about BMW risks is minimal, reducing community cooperation.
- Impact: Poor handling increases occupational hazards and undermines segregation efforts.

4. Weak Monitoring and Tracking:

- Manual record-keeping leads to unaccounted waste and non-compliance (CPCB, 2022).
- Limited regulatory inspections allow violations to go unchecked.
- Impact: Lack of transparency in the disposal chain risks public health and accountability.

5. Financial and Operational Constraints:

- Small healthcare facilities struggle to afford CBWTF services or on-site treatment systems.
- High operational costs deter investment in compliant infrastructure (MoEFCC, 2023).
- Impact: Cost-cutting leads to reliance on unregulated vendors or improper disposal.

Alternative Solutions

To address these challenges, innovative and sustainable alternatives can complement existing systems:

1. Treatment Systems:

- Deploy on-site treatment technologies like autoclaves, microwaves, or chemical disinfection for small facilities.
- Benefits: Reduces transport costs and risks, suitable for rural areas with limited CBWTF access.
- Example: Mobile treatment units for remote clinics.

2. Waste-to-Energy Technologies:

- Use advanced incineration, plasma pyrolysis, or gasification to convert non-infectious BMW into energy.
- Benefits: Minimizes landfill use and generates renewable energy (Datta et al., 2018).
- Example: Pilot projects in urban hospitals converting BMW into electricity.

3. Community-Based Models:

- Engage local communities in awareness campaigns to promote segregation and safe disposal.
- Benefits: Builds grassroots support and reduces improper disposal (Mathur et al., 2019).
- Example: NGO-led programs in rural India educating communities on BMW risks.

4. Technology-Driven Tracking:

- Implement IoT sensors, GPS, and blockchain for real time waste tracking from generation to disposal.
- Benefits: Enhances transparency, ensures compliance, and reduces illegal dumping (UNEP, 2020).
- Example: Digital platforms like those used in smart cities for waste monitoring. (Santhuja & Anbarasu, 2023)

5. Circular Economy Approach:

- Recycle non-hazardous BMW components (e.g., plastics, glass) after sterilization.
- Benefits: Reduces waste volume and promotes resource recovery.
- Example: Partnerships with recycling firms for treated BMW plastics (Rathee, 2025; NDMC, 2017).

Roadmap & Recommendations

To transform India's BMW management into a robust, sustainable system, the following roadmap and recommendations are proposed:

1. Enforce Segregation at Source

- Action: Mandate color-coded bins (yellow for infectious, red for plastics, blue for glass, white for sharps) in all healthcare facilities, with regular audits.
- Training: Conduct mandatory, annual training for healthcare workers on BMW categories and risks, certified by state health departments (Mathur et al., 2019).
- Penalties: Impose fines and license suspensions for non-compliance to deter violations.
- Timeline: Implement within 12 months, starting with urban hospitals and scaling to rural facilities.

2. Expand Centralized Biomedical Waste Treatment Facilities

- Action: Increase CBWTF coverage to 500 facilities by 2030, prioritizing rural and semi-urban areas.
- Funding: Offer government subsidies and low-interest loans to establish new CBWTFs (MoEFCC, 2023).
- Technology Upgrade: Retrofit existing facilities with eco-friendly technologies like plasma pyrolysis to reduce emissions (Datta et al., 2018).
- Timeline: Achieve 50% rural coverage by 2028, with upgrades completed by 2030.

3. Introduce Digital Tracking Systems

- Action: Develop a national digital platform integrating IoT, GPS, and blockchain for real time BMW tracking.
- Pilot Projects: Launch in 10 major cities by 2026, scaling nationwide by 2029.
- Stakeholder Collaboration: Partner with tech firms to ensure scalability and data security (UNEP, 2020).
- Benefits: Ensures traceability, reduces illegal dumping, and supports regulatory reporting.

4. Strengthen Private-Public Partnerships

- Action: Collaborate with private waste management companies to expand CBWTF networks and technology adoption.
- Incentives: Provide tax exemptions and land subsidies for private firms investing in compliant infrastructure.
- Regulatory Oversight: Establish joint monitoring committees to ensure PPPs meet BMW Rules, 2016 (CPCB, 2022).
- Timeline: Launch 50 PPP projects by 2027, covering 30% of BMW treatment capacity.

5. Capacity Building and Public Awareness

- Training Programs: Roll out nationwide workshops for healthcare workers and waste handlers, focusing on segregation and safety protocols.
- Public Campaigns: Use media, schools, and community centers to educate the public on BMW risks and segregation (Mathur et al., 2019).

- Funding: Allocate 5% of state health budgets to awareness and training by 2026.
- Timeline: Achieve 80% healthcare worker training coverage by 2028.

Implementation Framework

- **Stakeholders**: Central and state governments, healthcare facilities, CBWTF operators, private firms, NGOs, and communities.
- **Monitoring**: Establish a National Biomedical Waste Monitoring Authority to oversee compliance, track progress, and publish annual reports.
- **Funding**: Combine government budgets, PPP investments, and international grants (e.g., WHO, World Bank) for infrastructure and training.

Metrics for Success

- 90% segregation compliance by 2028.
- 100% rural CBWTF coverage by 2030.
- 50% reduction in illegal BMW dumping incidents by 2029.

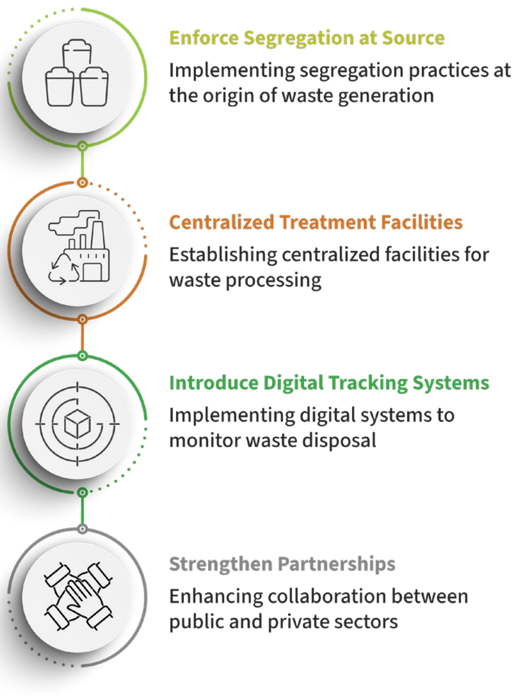


Figure 13: Biomedical Waste Management Strategies

India's biomedical waste management system faces significant challenges but also presents opportunities for innovation and reform. By enforcing segregation, expanding treatment infrastructure, leveraging digital tracking, fostering PPPs, and raising awareness, India can mitigate the risks posed by its 775 tonnes of daily BMW. Coordinated action among stakeholders, backed by robust policies and technology, is critical to building a safe, sustainable, and compliant BMW management ecosystem by 2030.

3.8 Textile Waste

Current Status & Problem Statement

India, a global textile powerhouse, discards approximately 1 million tonnes of textile waste annually, driven by its robust manufacturing sector and the rise of fast fashion. With recycling rates below 15%, most textile waste ends up in landfills or is incinerated, causing environmental degradation, resource loss, and health hazards. The absence of comprehensive policies, limited recycling infrastructure, and low consumer awareness exacerbate the crisis. This report provides an in-depth analysis of the current status of textile waste in India, identifies key challenges, explores innovative alternatives, and proposes a detailed roadmap with actionable recommendations to foster a circular textile economy.

India's textile industry, valued at over $150 billion, is the second-largest globally, contributing 7% to industrial output and employing over 45 million people. However, the sector generates lots of waste annually, including:

- **Post-Consumer Waste**: Discarded clothing and household textiles.
- **Pre-Consumer Waste**: Manufacturing scraps like fabric offcuts and defective products.
- **Industrial Waste**: Byproducts from textile processing, such as dyeing sludge.

Key issues in textile waste management include:

- **Low Recycling Rates**: Only 15% of textile waste is recycled, with the majority landfilled or incinerated (UNEP, 2020).
- **Environmental Impact**: Synthetic fibers like polyester release microplastics, while chemical dyes pollute water bodies.
- **Resource Loss**: Valuable materials like cotton, polyester, and wool are wasted, increasing reliance on virgin resources.

- **Informal Sector Challenges**: The informal sector, including ragpickers, handles much of the waste, leading to inefficiencies and unsafe working conditions (Bhattacharya, 2021).
- **Lack of Regulation**: Unlike biomedical waste, textile waste lacks mandatory policies like Extended Producer Responsibility (EPR), leaving manufacturers unaccountable for post-consumer waste.

These factors underscore the urgent need for systemic interventions to manage textile waste sustainably.

Challenges

1. Limited Recycling Infrastructure:

- India has few facilities for mechanical or chemical textile recycling, with most concentrated in urban hubs like Surat and Tirupur.
- Existing technologies struggle to process blended fabrics, limiting scalability (UNEP, 2020).
- Impact: High landfill dependency and environmental pollution from untreated waste.

2. Fast Fashion and Consumer Behavior:

- The rise of fast fashion fuels rapid clothing turnover, with consumers discarding garments after minimal use.
- Low awareness of sustainable disposal options discourages recycling or reuse (Bhattacharya, 2021).
- Impact: Increased waste volumes strain existing systems and exacerbate environmental harm.

3. Lack of Awareness and Education:

- Consumers are unaware of textile recycling benefits or second-hand markets.
- Manufacturers lack incentives to adopt sustainable practices or design recyclable products.
- Impact: Low participation in circular economy initiatives hinders progress.

4. Complex Material Composition:

- Modern textiles often combine natural (e.g., cotton) and synthetic (e.g., polyester, elastane) fibers, complicating recycling processes.
- Chemical recycling for blended fabrics is expensive and underdeveloped in India (World Bank, 2022).
- Impact: Reduced recycling feasibility increases landfill waste.

5. Weak Regulatory Framework:

- No mandatory EPR policies exist for textile manufacturers or brands, unlike in the EU.
- Limited enforcement of waste disposal regulations allows illegal dumping.
- Impact: Manufacturers have little accountability for post-consumer waste management.

Alternative Solutions

To address these challenges, innovative and scalable alternatives can transform textile waste management:

1. Mechanical Recycling:

- Shred textiles into fibers for new yarns or non-woven products like insulation, mattresses, or carpets.
- Benefits: Cost-effective for single-fiber textiles and reduces landfill use.
- Example: Recycling cotton scraps into yarn for affordable garments in Tirupur.

2. Chemical Recycling:

- Use depolymerization or solvent-based processes to break down synthetic fibers (e.g., polyester) into monomers for new textiles.
- Benefits: Enables recycling of blended fabrics and supports closed-loop systems.
- Example: Pilot projects by Indian startups converting polyester waste into new fibers.

3. Second-Hand and Upcycling Markets:

- Promote resale platforms, thrift stores, and upcycling initiatives to extend textile lifecycles.
- Benefits: Reduces waste, creates jobs, and encourages sustainable consumption.
- Example: Online platforms like OLX and designer upcycling brands in urban India.

4. Bio-Based and Biodegradable Textiles:

- Develop textiles from sustainable materials like hemp, organic cotton, or lyocell that decompose naturally.

- Benefits: Minimizes environmental impact and supports circularity.
- Example: Indian startups producing banana fiber-based fabrics (Nofal, 2022).

5. Digital Platforms for Waste Management:

- Create apps or platforms to connect consumers, recyclers, and manufacturers for efficient textile waste collection and processing.
- Benefits: Enhances transparency, streamlines collection, and engages communities.
- Example: Apps like Goonj for textile donation and recycling coordination.

Roadmap & Recommendations

To establish a sustainable textile waste management ecosystem in India, the following roadmap and recommendations are proposed:

1. Implement Extended Producer Responsibility:

- Action: Enact mandatory EPR policies requiring textile manufacturers and fashion brands to finance and manage post-consumer waste collection and recycling.
- Incentives: Provide tax exemptions for brands adopting sustainable designs (e.g., mono-material fabrics) and recycling programs.
- Stakeholder Engagement: Collaborate with industry bodies like the CITI to develop EPR guidelines.
- Timeline: Draft EPR policy by 2026, enforce for large brands by 2027, and extend to smaller manufacturers by 2029.

2. Promote Closed-Loop Recycling and Second-Hand Markets:

- Action: Subsidize closed-loop recycling facilities to process textiles into new products and support second-hand platforms through government-backed campaigns.
- Awareness Campaigns: Launch nationwide initiatives via social media, TV, and community events to promote thrift shopping and textile donation.
- Partnerships: Collaborate with e-commerce platforms like Myntra or Flipkart to integrate resale sections.
- Timeline: Achieve 30% closed-loop recycling capacity and 20% second-hand market penetration by 2030.

3. Invest in Textile Recycling Infrastructure:

- Action: Develop 50 new mechanical and chemical recycling plants by 2030, prioritizing textile hubs like Surat, Tirupur, and Panipat.
- Funding: Allocate $500 million through government budgets, private investments, and international grants (e.g., IFC, UNEP).
- Technology Adoption: Introduce advanced chemical recycling technologies for blended fabrics, with pilot projects in 5 cities by 2027.
- Timeline: Operationalize 20 plants by 2028, scaling to 50 by 2030.

4. Enhance Consumer and Industry Awareness:

- Action: Partner with NGOs, schools, and media to educate consumers on textile recycling, sustainable fashion, and waste reduction.
- Industry Training: Offer workshops for manufacturers on designing recyclable textiles and adopting circular practices.
- School Programs: Integrate textile waste education into curricula to foster sustainable habits among youth.
- Timeline: Reach 50% consumer awareness and train 70% of textile manufacturers by 2028.

5. Strengthen Regulatory Oversight and Monitoring:

- Action: Establish a National Textile Waste Authority to oversee compliance, track waste flows, and publish annual reports.
- Digital Tracking: Implement IoT and blockchain-based systems to monitor textile waste from collection to recycling.
- Penalties: Enforce fines and bans for illegal dumping and non-compliance with EPR policies.
- Timeline: Establish authority by 2026 and implement digital tracking systems by 2028.

Implementation Framework

- **Stakeholders**: Ministry of Textiles, NITI Aayog, MoEFCC, fashion brands, recycling firms, NGOs, informal sector workers, and consumers.
- **Monitoring**: Use digital platforms to track textile waste flows, recycling rates, and EPR compliance, with annual reports by the National Textile Waste Authority.
- **Funding**: Combine government budgets ($300 million), private investments ($150 million), and international grants ($50 million from UNEP, IFC) for infrastructure, technology, and awareness programs.
- **Metrics for Success:**

- Increase the textile recycling rate to 50% by 2030.

- Reduce textile waste in landfills by 40% by 2030.

- Establish 100 second-hand clothing outlets and 10 digital resale platforms in major cities by 2028.

- Achieve 90% EPR compliance among large brands by 2029.

India's textile waste crisis, with 1 million tonnes discarded annually, poses significant environmental, economic, and social challenges. By implementing EPR, promoting closed-loop recycling, investing in advanced infrastructure, raising awareness, and strengthening regulations, India can transition toward a circular textile economy. Coordinated efforts among government, industry, and communities, supported by innovative technologies and robust policies, are essential to reducing textile waste, conserving resources, and achieving sustainability goals by 2030.

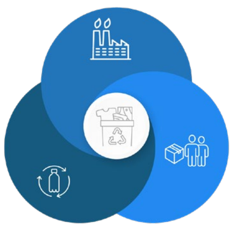


Figure 14: Strategies for reducing Textile Waste

3.9 Food Waste

India, a global agricultural powerhouse, discards over 50 million tonnes of food annually, equivalent to nearly 40% of its total food production (FAO, 2022). This staggering waste occurs across the supply chain, from production to consumption, exacerbating food insecurity for millions while contributing to environmental degradation through methane emissions and resource loss. Inefficient supply chains, consumer behaviour, limited processing infrastructure, and weak regulatory frameworks drive this crisis. This report provides a detailed analysis of the current state of food waste in India, identifies key challenges, explores innovative alternatives, and proposes a comprehensive roadmap with actionable recommendations to reduce food waste and foster a sustainable, circular food system.

Current Status & Problem Statement

India produces enough food to feed its 1.4 billion population, yet over 50 million tonnes of food are wasted annually, representing a significant economic, social, and environmental challenge (FAO, 2022). Food waste occurs at multiple stages:

- **Production and Harvesting**: Losses due to inefficient harvesting techniques, pest damage, and inadequate storage facilities.
- **Processing and Distribution**: Spoilage during transportation, poor cold chain infrastructure, and overstocking by wholesalers.
- **Consumer Level**: Over-purchasing, improper storage, discarding edible food due to aesthetic standards, and cultural practices like oversized servings at events.

Key issues include:

- **Food Security Paradox**: While 194 million Indians face undernourishment, edible food is discarded, undermining food security (FAO, 2022).
- **Environmental Impact**: Decomposing food waste in landfills generates methane, a greenhouse gas 25 times more potent than CO_2, contributing to 8% of India's emissions (UNEP, 2021).
- **Economic Loss**: Food waste results in an estimated $12 billion annual loss, including wasted water, energy, and labor (UNEP, 2021).

- **Infrastructure Gaps**: Limited composting or anaerobic digestion facilities restrict large-scale food waste processing, leading to landfill dependency (MoEFCC, 2023).
- **Lack of Policy**: Absence of mandatory food waste reduction or redistribution policies leaves stakeholders unaccountable.

Addressing food waste is critical to achieving SDGs 2 (Zero Hunger) and 12 (Responsible Consumption and Production) in India.

Challenges

1. Inefficient Supply Chain:

- Poor storage facilities, limited cold chain infrastructure, and inefficient logistics cause spoilage, particularly for perishable goods like fruits, vegetables, and dairy.
- Example: Over 30% of fruits and vegetables are lost post-harvest due to inadequate cold storage (FAO, 2022).
- **Impact**: Significant waste at the production and distribution stages.

2. Consumer Behavior and Cultural Practices:

- Urban consumers over-purchase food, discard edible items due to expiry dates or aesthetics, and lack awareness of proper storage.
- Cultural practices, such as large servings at weddings or festivals, contribute to waste (Bhattacharya, 2022).
- **Impact**: High household and event-based waste, particularly in urban areas.

3. Limited Processing Infrastructure:

- India has fewer than 200 large-scale composting or anaerobic digestion facilities, insufficient for processing 50 million tonnes of food waste (MoEFCC, 2023).
- Most municipalities rely on landfills, exacerbating methane emissions.
- **Impact**: Inability to manage food waste at scale leads to environmental harm.

4. Low Awareness and Education:

- Consumers, retailers, and food businesses lack knowledge about waste prevention, redistribution, or sustainable disposal methods.
- Limited public campaigns fail to engage communities in food waste reduction (Bhattacharya, 2022).
- **Impact**: Low participation in composting, redistribution, or prevention initiatives.

5. Weak Regulatory Framework:

- No national policy mandates food waste reduction or surplus redistribution, unlike in countries like France.
- Limited enforcement of existing waste management regulations allows illegal dumping (MoEFCC, 2023).
- **Impact**: Lack of accountability across the food supply chain hinders systemic change.

Alternative Solutions

To address these challenges, innovative and scalable solutions can transform food waste management:

1. Surplus Food Redistribution:

- Partner with NGOs, food banks, and community organizations to collect and distribute edible surplus food to vulnerable populations.
- **Benefits**: Reduces waste, addresses hunger, and strengthens community resilience.
- **Example**: Feeding India's network redistributes surplus from restaurants and events to shelters.

2. Composting:

- Establish decentralized and industrial composting facilities to convert food waste into organic fertilizer for agriculture.
- **Benefits**: Enriches soil, reduces landfill use, and supports sustainable farming.
- **Example**: Community composting units in Bengaluru's residential societies.

3. Anaerobic Digestion:

- Deploy bio-digesters to convert food waste into biogas for energy and digestate for fertilizer.
- **Benefits**: Generates renewable energy, reduces methane emissions, and creates agricultural inputs.
- **Example**: Biogas plants in Pune processing market and restaurant waste.

4. Food Waste Prevention Technologies:

- Use IoT-based sensors, smart inventory systems, and AI to monitor food freshness and optimize supply chain logistics.
- **Benefits**: Minimizes spoilage during storage and distribution.
- **Example**: Cold chain sensors tracking temperature for perishable goods.

5. Upcycling Food Waste:

- Transform inedible food waste (e.g., peels, seeds) into products like animal feed, bio-plastics, or biofuels.
- **Benefits**: Creates economic value and supports a circular economy.
- **Example**: Indian startups converting fruit peels into bio-based packaging or enzymes.

Roadmap & Recommendations

To establish a sustainable food waste management ecosystem in India, the following roadmap is proposed:

1. Mandate Surplus Food Redistribution Policies:

- **Action**: Enact policies requiring restaurants, hotels, and retailers in urban areas to donate edible surplus food to food banks or NGOs, with clear guidelines on safety and logistics.
- **Incentives**: Provide tax credits and certifications for businesses participating in redistribution programs.
- **Stakeholder Engagement**: Partner with organizations like Feeding India and Robin Hood Army to scale distribution networks.
- **Timeline**: Implement policies in 20 major cities by 2027, expanding nationwide by 2030.

2. Develop Bio-Digesters for Large-Scale Food Waste Treatment:

- **Action**: Establish 100 anaerobic digestion plants by 2030, focusing on urban centers and agricultural hubs with high food waste generation.
- **Funding**: Allocate $400 million through public-private partnerships and international grants (e.g., FAO, World Bank) for bio-digester infrastructure.
- **Technology Adoption**: Deploy modular bio-digesters for small-scale use in markets and communities.
- **Timeline**: Operationalize 30 plants by 2028, scaling to 100 by 2030.

3. Promote Awareness Campaigns on Food Waste Reduction:

- **Action**: Launch nationwide campaigns via social media, TV, radio, and community events to educate consumers on portion control, proper storage, and waste prevention.
- **School Programs**: Integrate food waste education into school curricula to foster sustainable habits among youth.
- **Partnerships**: Collaborate with influencers, chefs, and NGOs to promote campaigns like "Love Food, Hate Waste."
- **Timeline**: Achieve 60% consumer awareness by 2028, with 50% of schools adopting food waste curricula by 2029.

4. Strengthen Supply Chain Efficiency:

- **Action**: Invest in cold chain infrastructure, including refrigerated warehouses and transport, and deploy IoT-based monitoring to reduce spoilage.
- **Funding**: Allocate $500 million through PPPs and government budgets for supply chain upgrades.
- **Pilot Projects**: Test AI-driven inventory systems in 10 agricultural markets by 2027.
- **Timeline**: Upgrade 50% of cold chain infrastructure by 2029.

5. Introduce Regulatory Frameworks and Monitoring:

- **Action**: Develop a National Food Waste Reduction Policy mandating waste audits for large food businesses (e.g., supermarkets, hotels) and setting reduction targets of 25% by 2030.
- **Monitoring**: Establish a Food Waste Task Force to track progress, enforce compliance, and publish annual reports using digital platforms.
- **Penalties**: Impose fines for illegal dumping and non-compliance with waste reduction targets.
- **Timeline**: Draft policy by 2026, enforce audits by 2028, and achieve full compliance by 2030.

Implementation Framework

- **Stakeholders**: Ministry of Food Processing Industries, Ministry of Agriculture, MoEFCC, FSSAI, food businesses, NGOs, farmers, and consumers.
- **Monitoring**: Use IoT and blockchain-based platforms to track food waste volumes, redistribution rates, and bio-digester outputs, with annual reports by the Food Waste Task Force.
- **Funding**: Combine government budgets ($300 million), PPP investments ($150 million), and international grants ($50 million from FAO, UNEP, World Bank) for infrastructure, technology, and awareness programs.
- **Metrics for Success**:

- Reduce food waste by 25% (12.5 million tonnes) by 2030.

- Redistribute 10 million tonnes of surplus food annually to food-insecure communities by 2030.

- Establish 50 large-scale composting facilities and 100 bio-digester plants by 2030.

- Achieve 80% compliance with food waste audits among large businesses by 2029.

- Reach 70% consumer awareness of food waste prevention by 2028.

India's food waste crisis, with over 50 million tonnes discarded annually, undermines food security, environmental sustainability, and economic efficiency. By mandating surplus redistribution, developing bio-digester infrastructure, promoting awareness, improving supply chains, and enforcing robust regulations, India can significantly reduce food waste. Coordinated action among government, industry, and communities, supported by innovative technologies and policies, is essential to building a sustainable food waste management ecosystem aligned with SDGs 2 and 12 by 2030.

Food Waste Management Initiatives

Figure 15: Food Waste Management Initiatives

3.10 Sanitary Waste

Current Status & Problem Statement

India generates approximately 12 billion sanitary pads annually, alongside other sanitary products like tampons and diapers, creating significant environmental, public health, and social challenges due to improper disposal and limited sustainable management systems (CPCB, 2022). Predominantly non-biodegradable, this waste contributes to landfill overload, water and soil contamination, and health risks for waste handlers. Cultural taboos, inadequate infrastructure, and weak regulatory enforcement exacerbate the issue. This report provides a detailed analysis of the current state of sanitary waste in India, identifies key challenges, explores innovative alternatives, and proposes a comprehensive roadmap with actionable recommendations to foster a sustainable and inclusive sanitary waste management ecosystem.

India's increasing focus on menstrual hygiene, driven by government initiatives like the Swachh Bharat Mission and rising awareness, has led to widespread adoption of disposable sanitary products. These products, primarily composed of non-biodegradable materials such as superabsorbent polymers (SAPs), polyethylene, and polypropylene, pose significant disposal challenges. Key issues include:

- **Improper Disposal**: Sanitary waste is frequently discarded in household bins, open dumps, or water bodies, often wrapped in plastic bags, leading to sewage blockages and littering.

- **Environmental Impact**: Non-biodegradable pads take 500–800 years to decompose, releasing microplastics and chemicals into soil and groundwater. Open burning or unregulated incineration emits toxic pollutants like dioxins (Sharma et al., 2021).
- **Health Risks**: Waste handlers, often from marginalized communities, face exposure to pathogens and chemicals due to improper segregation and handling.
- **Social Stigma**: Cultural taboos around menstruation discourage open discussion and proper disposal, particularly in rural areas.
- **Infrastructure Gaps**: Limited dedicated collection and treatment systems, especially in rural and semi-urban areas, result in mismanagement of sanitary waste.

The Biomedical Waste Management Rules, 2016, classify sanitary waste as potentially infectious, mandating segregation and specialized disposal, but compliance is low, particularly in households, schools, and small healthcare facilities. This underscores the urgent need for systemic interventions to manage sanitary waste sustainably.

Challenges

1. Improper Disposal Practices:

- Many users, especially in rural areas, lack access to dedicated bins and dispose of sanitary waste with general waste or in open spaces like fields and rivers.
- Cultural practices, such as wrapping pads in plastic to conceal them, complicate waste segregation (Bhattacharya, 2022).
- Impact: Clogs sewage systems, pollutes water bodies, and increases health risks for waste handlers.

2. Non-Biodegradable Materials:

- Most sanitary pads contain 70–90% plastic-based materials (SAPs, polyethylene), making them unsuitable for composting or cost-effective recycling (CPCB, 2022).
- Limited research and development in biodegradable alternatives restrict market availability.
- Impact: Long-term environmental persistence and high landfill burden.

3. Limited Collection and Treatment Infrastructure:

- Few municipalities have segregated collection systems for sanitary waste, with only 10% of urban areas equipped with dedicated bins.
- Existing incinerators, often used in schools and hospitals, lack emission controls, releasing harmful pollutants.
- Impact: Inefficient waste management and environmental pollution.

4. Low Awareness and Cultural Stigma:

- Menstrual stigma discourages open discussion about proper disposal, leading to practices like flushing pads or burning them unsafely.
- Limited education on sustainable alternatives like menstrual cups or biodegradable pads hinders adoption (Sharma et al., 2021).
- Impact: Reduced compliance with segregation and low uptake of eco-friendly products.

5. Weak Regulatory Enforcement:

- The Biomedical Waste Management Rules, 2016, are poorly enforced for sanitary waste from households and non-healthcare settings.
- Absence of mandatory EPR policies leaves manufacturers unaccountable for post-consumer waste (CPCB, 2022).
- Impact: Lack of accountability and inconsistent waste management practices.

Alternative Solutions

To address these challenges, innovative and scalable solutions can transform sanitary waste management:

1. Biodegradable Sanitary Products:

- Develop and promote sanitary pads and tampons made from natural materials like bamboo, banana fiber, organic cotton, or water hyacinth.
- Benefits: Decomposes within 6–12 months, reduces landfill burden, and supports composting.
- Example: Indian brands like Saathi and Carmesi producing biodegradable pads.

2. Reusable Menstrual Products:

- Encourage adoption of menstrual cups, reusable cloth pads, and period underwear through subsidies and awareness campaigns.
- Benefits: Reduces waste generation by 90% over disposable products and lowers long-term costs for users.
- Example: Menstrual cup distribution programs in rural India by NGOs like Goonj.

3. Dedicated Collection Systems:

- Implement segregated collection systems with color-coded bins for sanitary waste in public toilets, schools, colleges, workplaces, and residential areas.
- Benefits: Ensures proper segregation, reduces mixing with general waste, and protects waste handlers.
- Example: Pilot projects in Pune and Delhi are installing sanitary waste bins in public facilities.

4. Advanced Treatment Technologies:

- Deploy eco-friendly incinerators with emission control systems or composting units for biodegradable sanitary waste.
- Benefits: Minimizes air pollution and enables safe disposal of infectious waste.
- Example: Low-emission incinerators in schools and hospitals in Tamil Nadu.

5. Recycling Innovations:

- Develop technologies to recycle sanitary waste plastics into products like fuel, construction materials, or plastic composites.
- Benefits: Reduces landfill waste and creates economic value from non-biodegradable components.
- Example: Pilot recycling plants in Mumbai processing sanitary pad plastics into fuel pellets.

Roadmap & Recommendations

To establish a sustainable sanitary waste management ecosystem in India, the following roadmap is proposed:

1. Promote Biodegradable Sanitary Products and Sustainable Alternatives:

- Action: Provide subsidies and tax exemptions to manufacturers of biodegradable pads and reusable products like menstrual cups and cloth pads.
- Awareness Campaigns: Launch nationwide programs targeting women and girls in schools, colleges, and rural communities to promote sustainable menstrual products, addressing stigma through inclusive messaging.
- Partnerships: Collaborate with NGOs, women's collectives, and health workers to distribute affordable, eco-friendly products.
- Timeline: Achieve 30% market penetration for biodegradable and reusable products by 2030, with 50% penetration in urban areas by 2028.

2. Set Up Dedicated Collection and Disposal Systems:

- Action: Install sanitary waste bins in public toilets, schools, colleges, workplaces, and residential societies, integrated with municipal collection systems for transport to treatment facilities.
- Funding: Allocate $150 million through public-private partnerships and government budgets for collection infrastructure.
- Training: Train waste handlers on safe handling and segregation to minimize health risks.
- Timeline: Establish collection systems in 50% of urban public facilities by 2028, scaling to 80% of urban and 50% of rural facilities by 2030.

3. Implement Producer Responsibility Programs:

- Action: Enforce EPR policies requiring sanitary product manufacturers to finance and manage the collection, treatment, and recycling of their products.
- Incentives: Offer tax benefits and certifications for manufacturers adopting biodegradable materials or establishing take-back programs.
- Stakeholder Engagement: Partner with industry bodies like the Indian Nonwovens and Technical Textiles Association to develop EPR guidelines.
- Timeline: Draft EPR policy by 2026, enforce for major brands by 2028, and extend to smaller manufacturers by 2030.

4. Enhance Treatment Infrastructure:

- Action: Develop 200 eco-friendly incineration

Roadmap for circular economy

Figure 16: Road Map of Sanitary Waste Management

and composting facilities for sanitary waste by 2030, prioritizing urban centers and menstrual hygiene hubs like Tamil Nadu and Uttar Pradesh.

- Technology Adoption: Deploy low-emission incinerators for non-biodegradable waste and composting units for biodegradable waste, with pilot projects in 10 cities by 2027.
- Funding: Allocate $200 million through PPPs and international grants (e.g., WHO, UNEP).
- Timeline: Operationalize 50 facilities by 2028, scaling to 200 by 2030.

5. Raise Awareness and Reduce Stigma:

- Action: Conduct campaigns via social media, TV, radio, schools, and community centers to educate on proper disposal, sustainable products, and menstrual health, emphasizing stigma reduction.
- School Programs: Integrate menstrual hygiene and waste management into curricula to reach adolescent girls.
- Community Engagement: Partner with NGOs, ASHA workers, and local leaders to conduct workshops in rural and marginalized communities.
- Timeline: Achieve 60% awareness among women and girls by 2028, with 80% of schools adopting menstrual waste education by 2030.

Implementation Framework

- **Stakeholders**: Ministry of Health and Family Welfare, Ministry of Environment, Forest and Climate Change, Central Pollution Control Board, sanitary product manufacturers, municipalities, NGOs, waste handlers, and communities.
- **Monitoring**: Establish a National Sanitary Waste Task Force to oversee compliance, track waste flows, and publish annual reports using IoT and blockchain-based platforms for transparency.
- **Funding**: Combine government budgets ($200 million), private investments ($100 million),

and international grants ($50 million from WHO, UNEP, World Bank) for infrastructure, technology, and awareness programs.

- **Metrics for Success**:

- Reduce non-biodegradable sanitary waste in landfills by 40% by 2030.

- Achieve 50% adoption of biodegradable or reusable menstrual products in urban areas and 30% in rural areas by 2030.

- Establish dedicated collection systems in 80% of public facilities and 50% of residential areas by 2030.

- Achieve 90% EPR compliance among manufacturers by 2029.

- Reach 70% awareness among women and girls on proper disposal and sustainable products by 2028.

India's sanitary waste crisis, with 12 billion pads generated annually, poses significant environmental, health, and social challenges due to non-biodegradable materials, improper disposal, and cultural stigma. By promoting biodegradable and reusable products, establishing dedicated collection and treatment systems, enforcing producer responsibility, and raising awareness, India can build a sustainable sanitary waste management ecosystem. Coordinated action among government, industry, and communities, supported by innovative technologies and robust policies, is critical to mitigating the impacts of sanitary waste and aligning with SDGs 3 (Good Health and Well-Being), 6 (Clean Water and Sanitation), and 12 (Responsible Consumption and Production) by 2030.

4

Integration with Climate Change Objectives

India, the world's third-largest emitter of greenhouse gases, faces the critical challenge of sustaining rapid economic growth while addressing climate change. Under the Paris Agreement, India has committed to reducing the emissions intensity of its GDP by 45% by 2030 (from 2005 levels), achieving 50% non-fossil fuel energy capacity, and reaching net-zero emissions by 2070. These ambitious targets require transformative approaches to decouple economic development from environmental degradation. The circular economy, which prioritizes reducing, reusing, and recycling resources, offers a robust framework to align India's economic and climate objectives. By minimizing waste, optimizing resource use, and reducing reliance on carbon-intensive processes, circular practices can drive decarbonization, support India's Nationally Determined Contributions (NDCs), and pave the way for carbon neutrality. This report provides an in-depth analysis of how circular economy practices contribute to climate goals, quantifies emission reductions, aligns with NDCs, and supports long-term carbon neutrality, with a focus on practical implementation in India's unique socio-economic context.

4.1 Circular Economy and Decarbonization

The circular economy challenges the linear "take-make-dispose" model by promoting resource efficiency, waste minimization, and material reuse. This paradigm shift is critical for decarbonization, as it reduces the carbon footprint of production and consumption across sectors. Key mechanisms include:

- **Reduced Demand for Raw Materials**: Extracting and processing raw materials, such as iron ore for steel or limestone for cement, accounts for approximately 25% of global CO_2 emissions. Circular practices, such as recycling steel or using industrial by-products like fly ash and slag, reduce the need for raw materials, lowering energy consumption and emissions. For example, recycling steel saves 60–75% of the energy required for primary production, reducing CO_2 emissions by 1.8 tonnes per tonne recycled. In India's steel industry, which produces 120 million tonnes annually, increasing recycled content to 30% could save 30–40 million tonnes of CO_2-equivalent (CO_2e) per year.
- **Waste Diversion from Landfills**: Organic waste in landfills generates methane, a potent GHG with a global warming potential 25 times higher than CO_2 over 100 years (IPCC], 2014). Circular interventions, such as composting, anaerobic digestion, and waste-to-energy (WtE) systems, divert organic waste, significantly reducing methane emissions. In India, where 50–60% of municipal solid waste (MSW) is organic, these practices could transform waste management into a climate solution (CPCB, 2020).
- **Energy-Efficient Recycling**: Recycling materials like aluminum, plastics, and paper consumes significantly less energy than primary production. For instance, recycling aluminum saves 95% of the energy required for virgin production, reducing CO_2 emissions by 15 tonnes per tonne. In India's aluminum sector, which consumes 2.5 million tonnes annually, a 50% recycling rate could save 15–20 million tonnes CO_2e per year.
- **Extended Product Lifecycles**: Repair, refurbishment, and sharing economy models extend product lifespans, reducing the need for new production. In the textile industry, reusing garments can cut emissions associated with cotton cultivation and synthetic fiber production by 20–30% (WRAP, 2017). India's textile sector, one of the largest globally, could reduce emissions by 10–15 million tonnes CO_2e annually through circular practices like second-hand markets and garment leasing.
- **Circular Business Models**: Models such as product-as-a-service (e.g., leasing electronics) and sharing platforms (e.g., carpooling) reduce resource consumption and emissions. In urban India, car-sharing platforms could reduce transport emissions by 5–10% by 2030.

In India, where industrial growth, urbanization, and population pressures drive resource consumption, circular practices can decarbonize high-emission sectors like cement, steel, textiles, and waste management. For example, in the cement industry, which accounts for 8% of India's GHG emissions, using recycled aggregates and alternative materials like fly ash can reduce emissions by 15–20% per tonne produced (CII, 2021).

4.2 Quantification of Emission Reductions

To evaluate the climate impact of circular economy practices, this section quantifies potential GHG reductions from key interventions in India, based on current waste generation, industrial output, and technological feasibility.

Reduced Landfill Methane Emissions

India generates approximately 150,000 tonnes of MSW daily, with 50–60% being organic (CPCB, 2020). Decomposing organic waste in landfills produces methane, contributing an estimated 16 million tonnes CO_2e annually. Circular interventions, such as composting and anaerobic digestion, can divert organic waste, reducing methane emissions by 60–70% (TERI, 2021).

If scaled nationwide, this could save 9.6–11.2 million tonnes CO_2e per year. Additionally, anaerobic digestion produces biogas, which can replace fossil fuels in cooking and power generation, further reducing emissions by 1–2 million tonnes CO_2e annually. For example, a biogas plant processing 100 tonnes of organic waste daily can produce 5,000 m^3 of biogas, offsetting 2,000 tonnes CO_2e per year (Ministry of New and Renewable Energy.

Recycling reduces emissions by substituting virgin materials with recycled ones, offering significant climate benefits:

- **Plastics**: India generates 9.5 million tonnes of plastic waste annually, with a recycling rate of only 20% (CPCB, 2020). Recycling 1 tonne of plastic saves 1.5–3.2 tonnes CO_2e, depending on the polymer type (EPA, 2021). Scaling the recycling rate to 50% could save 7–15 million tonnes CO_2e per year. For instance, recycling polyethylene terephthalate (PET) bottles reduces emissions by 2.1 tonnes CO_2e per tonne, and with 2 million tonnes of PET waste annually, a 50% recycling rate could save 2–3 million tonnes CO_2e (EPA, 2021).
- **Paper**: India produces 13 million tonnes of paper waste annually. Recycling at a 60% rate could save 0.7 tonnes CO_2e (IPMA, 2021). Paper recycling also reduces deforestation, enhancing carbon sinks.
- **Metals**: Recycling aluminum and steel from India's 10 million tonnes of metal waste could save 10–12 million tonnes CO_2e annually. Aluminum recycling, in particular, offers high savings due to its energy-intensive primary production (World Steel Association, 2021).
- **Textiles**: Recycling textiles, though less developed in India, could save 1–2 tonnes CO_2e per tonne. With 8 million tonnes of textile waste annually, a 30% recycling rate could save 2–5 million tonnes CO_2e (WRAP, 2020).

Plastic recycling | The disadvantages of Recycling

Alignment with India's NDCs

India's updated NDCs, submitted in 2022, commit to reducing emissions intensity by 45% by 2030, achieving 50% non-fossil fuel energy capacity, and creating a carbon sink of 2.5–3 billion tonnes CO_2e through afforestation (NDC, 2022) . Circular economy practices align with these targets by addressing emissions across multiple sectors:

- **Industrial Emissions Reduction**: Circular practices in energy-intensive sectors like cement, steel, and chemicals reduce emissions through material substitution and process efficiency. Using recycled scrap in steel production cuts emissions by 50–60% per tonne (World Steel Association, 2021). Scaling these practices could contribute 10–15% of the industrial emissions reductions needed for NDC compliance, equivalent to 50–70 million tonnes CO_2e by 2030.
- **Renewable Energy Integration**: Converting organic waste and agricultural residues into biogas, bioethanol, or biomass power supports India's 500 GW renewable energy target. Processing 50% of agricultural residue could produce 10–15 million tonnes of biofuels, saving 5–7 million tonnes CO_2e annually. Urban waste-to-biogas systems could contribute an additional 2–3 million tonnes CO_2e savings. (MNRE, 2021 ; NIBE Biomass Atlas; Singh et al., 2022)
- **Sustainable Urbanization**: India's *Smart Cities Mission* promotes waste segregation, recycling, and WtE, reducing emissions from urban waste management. Circular urban systems could save 3–5 million tonnes CO_2e annually by 2030, supporting low-carbon cities (NIUA, 2019). For example, Pune's waste management model, which integrates segregation and composting, has reduced emissions by 0.5 million tonnes CO_2e annually (NIUA, 2021).
- **Carbon Sinks**: Composting organic waste and applying biochar enhance soil carbon sequestration, supporting India's afforestation and soil restoration goals. Scaling composting to 50% of organic waste could sequester 1–2 million tonnes CO_2e per year, while biochar could add 1–3 million tonnes CO_2e (TERI, 2021).
- **Cross-Sectoral Synergies**: Circular practices in construction, textiles, and electronics reduce emissions while promoting resource efficiency, aligning with NDC goals for sustainable development. For instance, modular construction techniques could reduce emissions by 10–15% in India's construction sector.

By 2030, circular economy practices could contribute 15–20% of the emissions reductions required to meet NDC targets, particularly in waste, industrial, and energy sectors, equivalent to 100–150 million tonnes CO_2e annually . These practices also enhance climate resilience by reducing resource dependence and environmental degradation.

4.3 GHG Mitigation Potential across Sectors

Circular economy practices offer substantial GHG mitigation potential across India's economy, with impacts in the following sectors:

- **Waste Management**: Landfill diversion, recycling, and WtE could reduce 15–25 million tonnes CO_2e annually by 2030, equivalent to 5–7% of India's waste sector emissions (MoEFCC, 2021).
- **Industry**: Using recycled materials in manufacturing (e.g., steel, cement, plastics) could save 10–12 million tonnes CO_2e per year. For example, incorporating 30% recycled aggregates in cement production could reduce emissions by approximately 8–10 million tonnes CO_2e annually, addressing the cement sector's 8% share of national emissions (CII, 2021).
- **Agriculture**: Circular bio economy practices, such as converting crop residues into biofuels or biochar, could mitigate 5–7 million tonnes CO_2e per year. Biochar application also enhances soil fertility, reducing the need for synthetic fertilizers, which contribute 5% of agricultural emissions.
- **Construction**: Recycling C&D waste and adopting modular construction techniques could save 10–15 million tonnes CO_2e per year, addressing the construction sector's 10% share of national emissions. Modular designs, which minimize material waste, could reduce emissions by 20–30% in urban projects (MOEFCC, 2020).
- **Textiles and Electronics**: Recycling textiles and e-waste, though nascent in India, could

save 3–5 million tonnes CO_2e annually by 2030. For example, recycling 30% of India's 2 million tonnes of e-waste could save 1–2 million tonnes CO_2e.

A comprehensive study by TERI estimates that circular economy adoption could reduce India's total GHG emissions by 10–11% by 2030, indicating emissions reduction equivalent to 200–300 million tonnes CO_2e annually depending on sectoral interventions and appropriate scaling (TERI, 2021). This reduction is critical for aligning with India's NDC targets and global climate goals under the Paris Agreement.

4.4 Role in Achieving Carbon Neutrality

India's commitment to net-zero emissions by 2070 requires systemic decarbonization across all sectors, coupled with enhanced carbon sequestration. The circular economy plays a pivotal role in this transition by:

- **Lowering Sectoral Carbon Footprints**: Circular practices reduce emissions in high-impact sectors like construction (10% of emissions), industry (30%), and waste (5%) (MoEFCC, 2020). For example, modular construction and recycled materials could cut construction emissions by 20–30% by 2050, saving 30–40 million tonnes CO_2e annually (CII, 2021). Similarly, recycling in the steel and cement industries could reduce emissions by 50–70 million tonnes CO_2e per year by 2050 (World Steel Association, 2021).
- **Enhancing Carbon Sequestration**: Composting organic waste and applying biochar improve soil carbon storage, contributing to India's carbon sink goals. Scaling these practices could sequester 3–5 million tonnes CO_2e annually by 2050, supporting afforestation efforts (TERI, 2021). For instance, biochar application in 10% of India's agricultural land could sequester an estimated value of 2–3 million tonnes CO_2e per year.
- **Promoting Low-Carbon Business Models**: Circular models, such as product-as-a-service (e.g., leasing electronics) and sharing platforms (e.g., carpooling), reduce consumption-driven emissions. These models could cut urban transport emissions by 5–10% by 2040, saving 20–30 million tonnes CO_2e annually in cities like Delhi and Mumbai.
- **Supporting Energy Transition**: WtE and bioenergy from waste and agricultural residues can replace 5–10% of India's fossil fuel-based energy by 2050, reducing emissions by 50–100 million tonnes CO_2e annually (MNRE, 2021). For example, scaling bioenergy to 50 GW by 2050 could replace 10% of coal-based power, a critical step toward decarbonization (MNRE, 2021).
- **Fostering Innovation and Resilience**: Circular practices encourage innovation in materials, processes, and business models, enhancing India's resilience to climate impacts like floods and heatwaves. For instance, circular urban waste management reduces landfill pressure, mitigating flood risks in monsoon-prone cities (NIUA, 2021).

By integrating circular practices across sectors, India can achieve significant emission reductions while building a resilient, low-carbon economy. For example, circular construction practices could reduce emissions by 30–40 million tonnes CO_2e per year by 2050, supporting India's net-zero pathway (CII, 2021). Similarly, scaling bioenergy and WtE could replace 10–15% of coal-based power, reducing emissions by 100–150 million tonnes CO_2e annually by 2070 (MNRE, 2021)

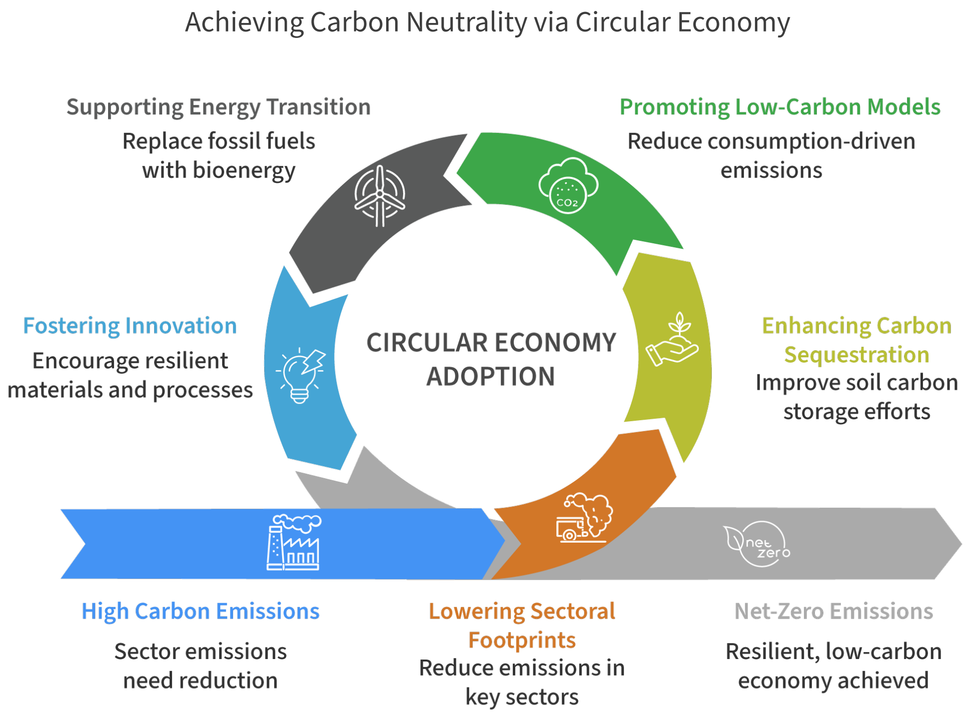


Figure 17: Carbon Neutrality through Circular Economy

5 Role of Technology and Innovation: Contributions of AI and IoT

The integration of technology and innovation, particularly through Artificial Intelligence (AI) and the Internet of Things (IoT), has revolutionized conventional waste management systems by transforming them into data-driven, intelligent, and sustainable frameworks. These technologies not only enhance operational efficiency and resource optimization but also play a pivotal role in facilitating the transition towards a circular economy.

5.1 Artificial Intelligence (AI) in Waste Management

AI has demonstrated significant potential across multiple stages of waste management, including collection, monitoring, segregation, recycling, landfill optimization, and strategic planning. The implementation of AI-based solutions is instrumental in scaling up infrastructure development cost-effectively and sustainably (Sharma et al., 2023).

Widely used AI models - such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Decision Trees (DT), and Genetic Algorithms (GA) - have been applied for predicting waste generation patterns, monitoring bin fill levels, optimizing collection routes, identifying illegal dumping sites, and improving the overall planning and performance of waste management systems (Abdallah et al., 2020; Andeobu et al., 2022).

AI-based waste classification systems have particularly advanced material recovery efficiency. For instance, (M. Kumar et al., 2023) applied NIR hyperspectral imaging combined with image segmentation and a feedforward neural network to classify plastic polymers with accuracy of 89.5%. Despite the challenges posed by mixed or contaminated waste streams and computational complexity, AI models - especially hybrid models like CNN combined with MLP - have achieved classification accuracies exceeding 98% (Chu et al., 2018). These models have consistently outperformed standalone classifiers such as CNN, SVM, and RF, particularly when trained on large and diverse datasets (Kuritcyn et al., 2015; Abdallah et al., 2020).

In the Indian context, where proper segregation of waste remains a major challenge, AI can support resource recovery by enabling efficient and scalable waste sorting. Several studies have also demonstrated the application of AI for predicting waste generation based on demographic and socio-economic indicators (Ysabel et al., 2008; Korhonen & Kaila, 2015).

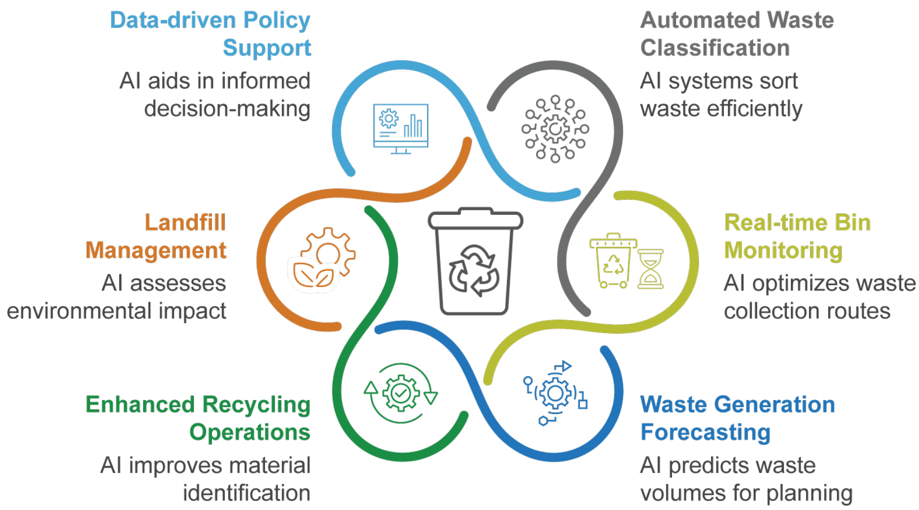


Figure 18: AI in Waste Management Applications (Sharma, 2023; Marković & Jemović, 2024):

5.2 Internet of Things (IoT) in Waste Management

The IoT complements AI by enabling real time monitoring, automated control, and seamless data exchange through networked sensors and devices. IoT applications in waste management facilitate predictive analytics, automation, and integration with smart city infrastructure, aligning with circular economy principles.

Key contributions of IoT in waste management include:

- **Smart Bins and Fill-Level Sensors:** Enable real time tracking of bin status, reducing unnecessary collections and improving efficiency (Rihm et al., 2024).
- **Intelligent Collection Systems:** Use location and bin-fill data to optimize collection routes and reduce emissions (Goran et al., 2024; IoT-Based Route Recommendation, 2022).
- **Automated Waste Segregation:** Devices embedded with sensors sort waste based on type, improving material recovery (Raut, 2024; Singh et al., 2024).
- **Predictive Maintenance:** IoT sensors monitor equipment performance, preventing breakdowns and optimizing lifecycle costs (Bonala et al., 2024; Vashishth et al., 2024).
- **Urban Resource Mapping:** Supports circular use of materials through spatial tracking and efficient resource allocation (Munonye & Ajonye, 2024).
- IoT devices also support strategic planning by generating high-resolution datasets, which can be further analysed using AI models to improve operational and environmental outcomes.

5.3 Implementation, Benefits, and Challenges

Several global case studies underscore the practical advantages of AI and IoT in waste management. For instance, in Beijing, the deployment of a smart waste management system reduced instances of bin overflow and decreased collection frequency, demonstrating improved system efficiency (Yao et al., 2024).

Despite these benefits, some challenges remain. High initial infrastructure costs, lack of interoperability among devices, and concerns about data privacy and cybersecurity can impede large-scale adoption. Additionally, the successful deployment of these technologies requires coordinated efforts across government, industry, and civil society (Sharma, 2023).

Nevertheless, the synergistic use of AI and IoT continues to drive significant advancements in waste management efficiency, transparency, and sustainability - paving the way for a circular economy.

5.4 AI and IoT-Based Roadmap for Municipal Solid Waste Management in India

A comprehensive and **practical roadmap** for integrating **Artificial Intelligence (AI)** and the **Internet of Things (IoT)** to manage municipal **solid waste across all major waste streams in India is given as follows.** This roadmap considers India's socio-economic diversity, infrastructure constraints, and policy framework, and offers **feasible, step-wise recommendations** aligned with circular economy goals.

Vision

To develop a unified, intelligent, and efficient waste management ecosystem across India by leveraging AI and IoT technologies for better collection, segregation, processing, and resource recovery from all major waste streams.

Phase-Wise Roadmap

Phase 1: Digital Infrastructure & Data Foundation (Years 1–2)

Goal: Establish the digital backbone

Focus Areas:
- Municipal Solid Waste
- Biomedical Waste
- E-Waste

Recommendations

1. Nationwide GIS & RFID-based Waste Mapping:

- Implement geotagged smart bins and GPS-

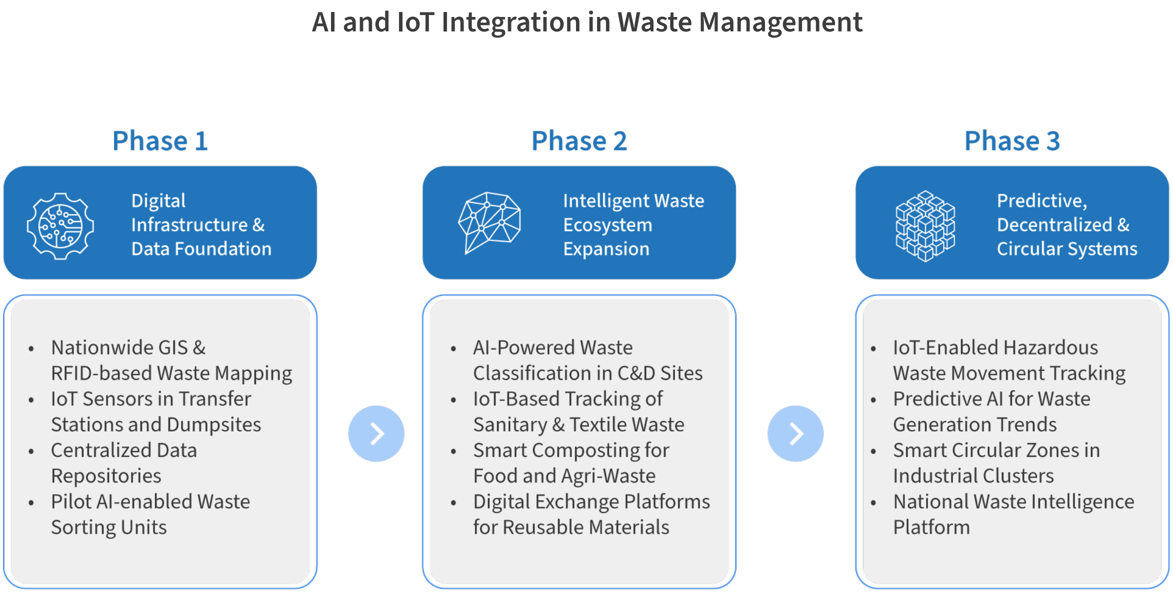


Figure 19: AI & IoT Road Map for Waste Management

fitted collection vehicles in Tier 1 and Tier 2 cities.

- Integrate with ULB dashboards using the Swachh Bharat Urban digital platform.

2. IoT Sensors in Transfer Stations and Dumpsites:

- Monitor fill levels, temperature (for biomedical), and toxic gas emissions.
- Real time alerts to prevent overflows or unsafe handling.

3. Centralized Data Repositories:

- Mandate digital waste tracking and analytics portals, starting with e-waste and biomedical waste (already partially in use).

4. Pilot AI-enabled Waste Sorting Units:

- Test robotic and vision-based sorting at MRFs in metro cities.

Feasibility

Leverages existing smart city infrastructure and MoEFCC/CPCB guidelines. Initial pilot funding through **Smart Cities Mission** and **state urban development funds**.

Phase 2: Intelligent Waste Ecosystem Expansion (Years 3–5)

Goal: Scale AI/IoT for real time decision-making and automation

Focus Areas:

- Construction & Demolition (C&D) Waste
- Textile and Sanitary Waste
- Food and Agricultural Waste

Recommendations

1. AI-Powered Waste Classification in C&D Sites:

- Drones and vision systems to identify concrete, wood, metal, etc. for reuse or recycling.

2. IoT-Based Tracking of Sanitary & Textile Waste:

- Use color-coded smart bins and QR-tagged waste for targeted collection in residential and commercial areas.

3. Smart Composting for Food and Agri-Waste:

- IoT-enabled compost bins at household/ community levels to monitor moisture, pH, and gas emissions.
- AI models to optimize composting cycles and volume estimation.

4. Digital Exchange Platforms for Reusable Materials:

- AI-curated marketplaces (like **Recykal**) for selling reusable C&D and textile materials to industries.

Feasibility

Builds on Phase 1 data foundation. Collaborate with **state pollution control boards, private recyclers**, and **agritech start-ups**. Leverage CSR and circular economy funds.

Phase 3: Predictive, Decentralized & Circular Systems (Years 5–7)

Goal: Full-cycle integration of AI & IoT for resource recovery

Focus Areas:

- Hazardous Waste
- Mixed-Use Waste Streams
- Interlinking All Waste Categories

Recommendations

1. IoT-Enabled Hazardous Waste Movement Tracking:

- GPS and RFID-based manifests for cradle-to-grave monitoring of industrial, chemical, and biomedical waste.

2. Predictive AI for Waste Generation Trends:

- Use satellite, consumption, and urbanization data to forecast waste hotspots.
- Dynamic deployment of waste infrastructure (MRFs, bins, transport).

3. Smart Circular Zones in Industrial Clusters:

- AI-managed industrial symbiosis models to divert hazardous by-products for reuse in other industries.

4. National Waste Intelligence Platform:

- Integrate all waste stream data (MSW, e-waste, agri, hazardous) into a central analytics hub for planning, compliance, and climate reporting (linking to India's **Biennial Transparency Reports** and SDGs).

Feasibility

Requires central government coordination (MoEFCC, CPCB, NITI Aayog) with localized deployment. Can be funded under the **National Circular Economy Framework, Atmanirbhar Bharat**, and **Climate Action Plans.**

Table 2: Cross-Cutting Enablers

Enabler	Action
Policy & Regulation	Mandate digital tracking and AI-based planning for all waste ULBs and SPCBs. Introduce incentives for AI/IoT adoption in waste start-ups.
Capacity Building	Train ULBs, rag pickers, and recyclers on tech use. Establish AI/IoT skill hubs under Skill India.
Public Awareness	Promote citizen engagement via apps that reward source segregation, report illegal dumping, and visualize local waste metrics.
R&D and Innovation	Fund AI/IoT R&D in waste through DBT, DST, and SERB. Encourage academia-industry start-up collaboration.

Key Outcomes by 2030 (If Roadmap is followed):

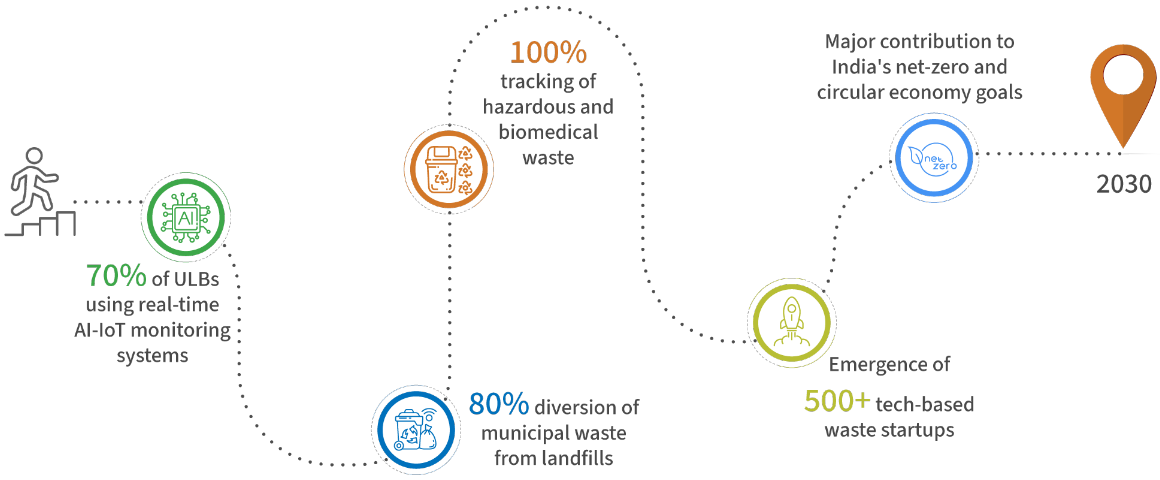
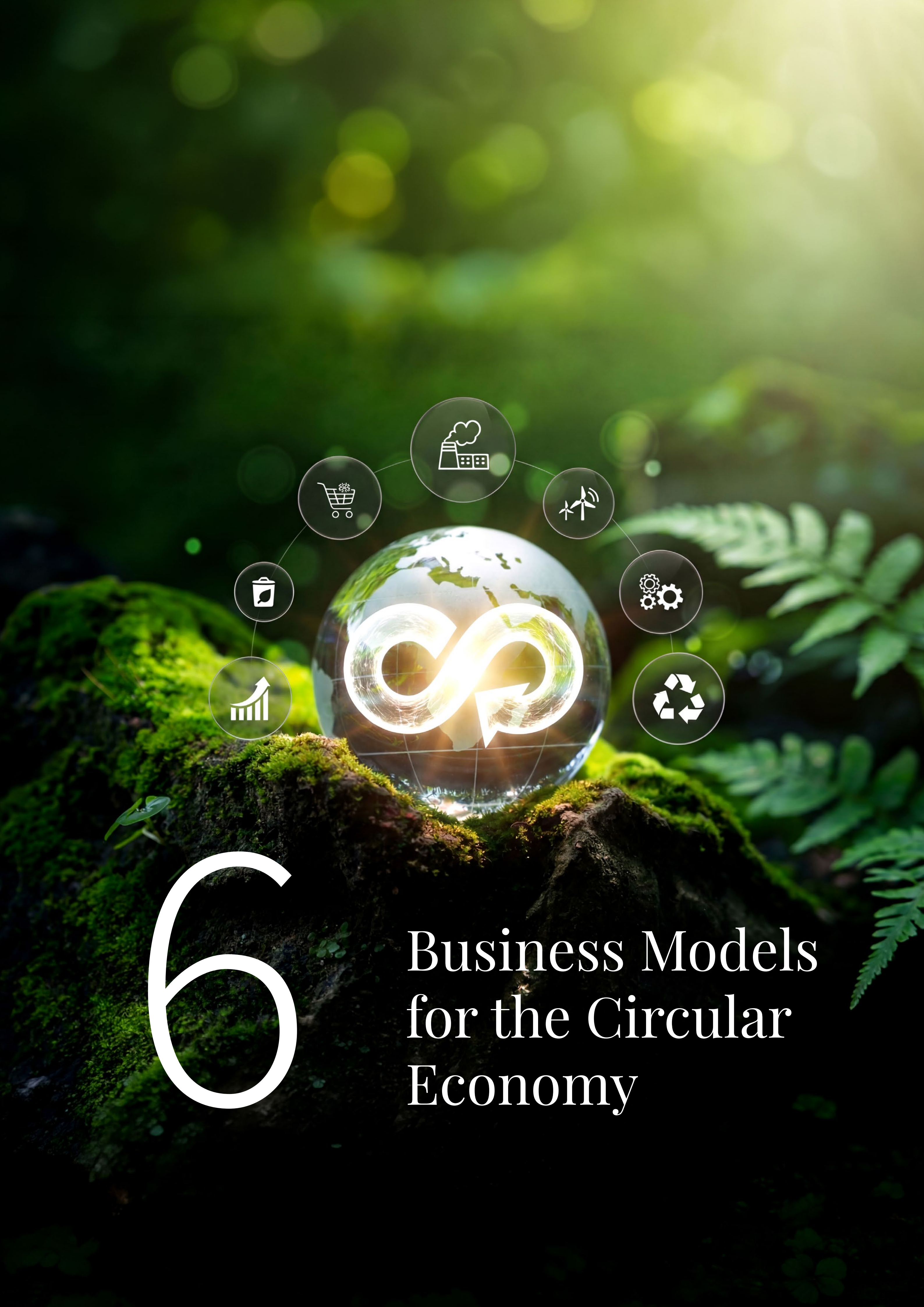


Figure 20: Key Outcomes by 2030



6 Business Models for the Circular Economy

The circular economy represents a transformative approach that prioritizes resource efficiency, waste minimization, and long-term sustainability by moving beyond the traditional “take–make–dispose” model. It emphasizes designing out waste, keeping materials in use, and regenerating natural systems. This chapter examines key circular business models, opportunities for MSMEs and start-ups, financing mechanisms, public-private partnerships, and the role of carbon markets. It also highlights the importance of industry participation, investment in recycling infrastructure, and market development for secondary materials to enable scalable and sustainable circular business ecosystems.

6.1 Examples of Circular Business Models

1. Sharing Economy

The sharing economy leverages underutilized assets by enabling shared access to goods and services, reducing the need for ownership and extending product lifecycles. Platforms like Airbnb and Zipcar exemplify this model, allowing individuals to rent homes or vehicles, respectively, instead of purchasing them. The Ellen MacArthur Foundation highlights that sharing models can reduce resource consumption by up to 20% in sectors like transportation and housing. For instance, car-sharing services decrease the demand for new vehicle production, lowering material use and emissions. Businesses adopting this model benefit from scalable platforms and recurring revenue, while consumers gain cost-effective access to high-value assets.

2. Product-as-a-Service

In the PaaS model, companies retain ownership of products and offer their use as a service, incentivizing durability and maintenance. For example, Philips’ “Light as a Service” provides lighting solutions where customers pay for illumination rather than purchasing bulbs. This model encourages manufacturers to design long-lasting, recyclable products, as they bear the cost of maintenance and end-of-life management. The Ellen MacArthur Foundation notes that PaaS can reduce material inputs by 30–50% in industries like electronics and appliances. PaaS also fosters customer loyalty through subscription-based revenue streams.

CIRCULAR ECONOMY BUSINESS MODELS COMPARISON

CHARACTERISTIC	SHARING ECONOMY	PRODUCT-AS-A-SERVICE (PAAS)	REVERSE LOGISTICS
CORE FUNCTION	Shared access to assets	Product use as a service	Recovery of used products
OWNERSHIP	Users access assets, ownership varies	Company retains product ownership	Ownership transferred back to company
KEY BENEFITS	Reduces need for ownership	Incentivizes durability and maintenance	Reduces waste and raw material use
EXAMPLE	Airbnb, Zipcar	Philips’ "Light as a Service"	Patagonia take-back programs
ECONOMIC IMPACT	Scalable platforms, recurring revenue	Subscription-based revenue streams	Cuts production costs

Figure 21: Comparison of Circular Economy Business Models

3. Reverse Logistics

Reverse logistics involves recovering used products or materials for reuse, refurbishment, or recycling. Companies like Patagonia implement take-back programs, collecting worn clothing for repair or recycling into new products. This model closes the loop on resource flows, reducing waste and raw material extraction. According to the Ellen MacArthur Foundation, reverse logistics can cut production costs by 10–15% through material recovery. It also enhances brand reputation by aligning with consumer demand for sustainable practices. Effective reverse logistics requires robust supply chain coordination and consumer engagement to ensure product returns.

6.2 Opportunities for Start-ups and MSMEs

Start-ups and MSMEs are uniquely positioned to drive circular economy initiatives due to their agility and ability to innovate. NITI Aayog's guidelines on start-up ecosystems emphasize the need for supportive policies, access to funding, and market linkages to scale circular ventures. Key opportunities include:

- **Niche Markets**: Start-ups can target underserved segments, such as biodegradable packaging or upcycled fashion. For instance, India-based start-up BhuSattva creates textiles from agricultural waste, tapping into growing demand for sustainable materials.
- **Digital Platforms**: MSMEs can develop apps or platforms to facilitate sharing or second-hand markets. For example, OLX India enables peer-to-peer sales of used goods, extending product lifecycles.
- **Localized Solutions**: MSMEs can address region-specific waste challenges, such as composting organic waste in rural areas or recycling plastics in urban centres. Small-scale biogas plants, supported by NITI Aayog's start-up schemes, convert food waste into energy for local communities.
- **Collaborative Networks**: Start-ups can partner with larger firms for reverse logistics or material sourcing. For example, MSMEs supplying recycled plastics to FMCG companies benefit from stable demand and technical support.

NITI Aayog's Atal Innovation Mission and Start-up India provide mentorship, grants, and incubation support to circular economy ventures, enabling MSMEs to overcome barriers like high initial costs and market entry challenges.

6.3 Financing Mechanisms and Public-Private Partnerships

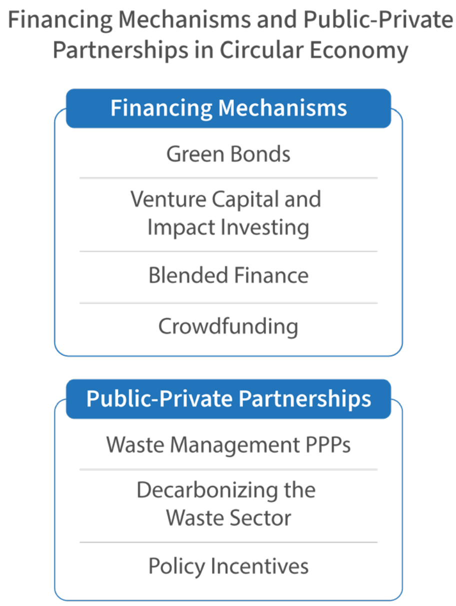


Figure 22: Private-Public Partnership and Finance in CE

1. Financing Mechanisms

Scaling circular business models requires innovative financing to address high upfront costs and long payback periods. Key mechanisms include:

- **Green Bonds**: These debt instruments fund projects with environmental benefits, such as recycling facilities or renewable energy systems. Globally, green bond issuance reached $500 billion in 2024, with India emerging as a key market.
- **Venture Capital and Impact Investing**: Investors are increasingly backing circular start-ups, particularly in waste-to-value and clean tech. For example, Circulate Capital has invested in Indian start-ups tackling plastic waste.

- **Blended Finance**: Combining public and private funds reduces risks for circular projects. The World Bank's blended finance programs support MSMEs in waste management and renewable energy.
- **Crowdfunding**: Platforms like Ketto enable start-ups to raise funds for circular initiatives, such as community recycling programs, by engaging environmentally conscious consumers.

2. Public-Private Partnerships

PPPs are critical for aligning public policy with private sector innovation. In the circular economy, PPPs facilitate infrastructure development, technology adoption, and market creation. Examples include:

- **Waste Management PPPs**: In India, municipal corporations partner with private firms to manage municipal solid waste. For instance, the Indore Municipal Corporation collaborates with waste-to-energy companies to process 1,000 tons of waste daily, generating biogas and compost.
- **Decarbonizing the Waste Sector**: PPPs support projects like anaerobic digestion plants, which convert organic waste into biogas, reducing methane emissions. The Ellen MacArthur Foundation estimates that such initiatives could cut global waste sector emissions by 25% by 2030.
- **Policy Incentives**: Governments provide tax breaks or subsidies to private partners adopting circular practices. NITI Aayog's circular economy roadmap advocates for PPPs to develop recycling hubs, creating jobs and reducing landfill dependency.

6.4 Circular and Low-Carbon Business Models

Circular business models inherently contribute to low-carbon outcomes by minimizing resource use and waste. Specific low-carbon models include:

- **Remanufacturing**: Companies like Caterpillar remanufacture heavy machinery, reducing energy use by 50% compared to new production. In India, MSMEs can adopt remanufacturing for automotive parts, lowering costs and emissions.
- **Bio-based Materials**: Businesses producing bio-plastics or organic fertilizers from agricultural waste reduce reliance on fossil-based materials. For example, Indian start-up Bio Prime develops bio-fertilizers that enhance soil health and sequester carbon.
- **Energy Recovery**: Waste-to-energy models, such as incineration or biogas production, convert non-recyclable waste into power. These models align with India's Swachh Bharat Mission, which promotes clean energy from urban waste.

These models not only reduce greenhouse gas emissions but also create economic value by turning waste into resources. The Ellen MacArthur Foundation projects that circular practices could reduce global CO2 emissions by 40% by 2050.

6.5 Carbon Credit Markets and Incentives for Waste-to-Value Projects

Carbon credit markets incentivize circular and low-carbon projects by monetizing emission reductions. In waste-to-value initiatives, carbon credits are generated through activities like methane capture, recycling, or energy recovery. Key aspects include:

- **Market Mechanisms**: Voluntary carbon markets, such as Verra and Gold Standard, certify credits from waste management projects. For example, a biogas plant in India can earn credits by reducing methane emissions, which are sold to corporates offsetting their emissions.
- **Incentives**: Governments offer subsidies or feed-in tariffs for waste-to-energy projects. India's Ministry of New and Renewable Energy provides financial support for biogas plants, enhancing project viability.
- **Challenges**: High certification costs and complex verification processes can deter MSMEs. NITI Aayog recommends simplifying standards and providing technical assistance to small-scale projects.
- **Case Study**: Saahas Zero Waste, an Indian social enterprise, earns carbon credits by diverting 50,000 tons of waste annually from landfills through recycling and composting.

The credits fund further expansion, creating a virtuous cycle.

Carbon markets are expected to grow, with global demand for credits projected to reach $50 billion by 2030, offering significant opportunities for circular economy ventures.

The circular economy offers a blueprint for sustainable growth, with business models like the sharing economy, product-as-a-service, and reverse logistics driving resource efficiency and waste reduction. Start-ups and MSMEs can capitalize on niche markets, digital platforms, and localized solutions, supported by NITI Aayog's start-up ecosystems. Financing mechanisms, including green bonds and blended finance, alongside PPPs, enable the scaling of circular initiatives, particularly in waste management and decarbonization. Carbon credit markets further incentivize waste-to-value projects, aligning economic and environmental goals. By adopting these models and leveraging partnerships, businesses can transition to a low-carbon, circular future, contributing to global sustainability targets.

7 Decarbonization Strategy for Circular Economy

The circular economy, with its focus on resource efficiency, waste minimization, and material reuse, offers a powerful framework for addressing climate change. By integrating decarbonization strategies, the circular economy can significantly reduce GHG emissions while fostering economic resilience. This report presents a roadmap for embedding decarbonization into the circular economy, emphasizing low carbon material alternatives, energy efficiency in waste processing, electrification of waste collection fleets, and alignment with India's renewable energy goals. Drawing on IPCC reports and India's MoEFCC documents, the strategy outlines actionable steps for stakeholders, including policymakers, businesses, and municipalities, to achieve a low-carbon, circular future.

7.1 Roadmap for Integrating Decarbonization into the Circular Economy

The roadmap for decarbonizing the circular economy is structured around four pillars: material innovation, process optimization, fleet electrification, and renewable energy integration. Each pillar includes short-term (1–3 years), medium-term (3–7 years), and long-term (7–15 years) actions to ensure progressive implementation.

Pillar 1: Material Innovation

Objective: Transition to low-carbon materials to reduce embodied emissions in products and packaging.

- **Short-Term**: Promote bio-based plastics and recycled materials in high-impact sectors like packaging and textiles. Pilot projects with MSMEs to test scalability.
- **Medium-Term**: Develop standards for low-carbon materials, supported by incentives like tax breaks. Establish MRFs to increase recycled material supply.
- **Long-Term**: Achieve 50% market penetration of bio-based and recycled materials in India's manufacturing sector by 2040, aligning with MoEFCC's net-zero targets.

Pillar 2: Process Optimization

Objective: Enhance energy efficiency in waste processing to minimize emissions.

- **Short-Term**: Conduct energy audits in waste processing facilities to identify inefficiencies. Retrofit facilities with energy-efficient equipment.
- **Medium-Term**: Adopt advanced technologies like anaerobic digestion and automated sorting to reduce energy use. Train workers on energy management practices.
- **Long-Term**: Integrate IoT systems for real time energy monitoring, achieving a 30% reduction in energy consumption by 2035.

Pillar 3: Fleet Electrification

Objective: Electrify waste collection fleets to eliminate fossil fuel emissions.

- **Short-Term**: Pilot EV waste collection trucks in urban centers like Delhi and Bengaluru. Secure funding through green bonds.
- **Medium-Term**: Expand EV fleets to 50% of municipal waste collection vehicles by 2030, supported by charging infrastructure.
- **Long-Term**: Achieve 100% electrification of waste collection fleets by 2040, integrated with renewable energy-powered charging stations.

Pillar 4: Renewable Energy Integration

Objective: Power circular economy activities with renewable energy, focusing on WTE projects.

- **Short-Term**: Map existing WTE plants and assess their renewable energy potential. Launch pilot projects for solar-powered waste processing.
- **Medium-Term**: Scale WTE projects using biogas and biomass, aligned with India's renewable energy target of 500 GW by 2030.
- **Long-Term**: Ensure all WTE facilities operate on 100% renewable energy by 2040, contributing to India's net-zero goal by 2070.

This roadmap aligns with the IPCC's emphasis on systemic changes in waste management to achieve deep emission cuts, as outlined in its 2022 report, and the MoEFCC's climate mitigation strategies for sustainable urban development.

Achieving Decarbonization in Circular Economy

Figure 23: Decarbonization in CE

7.2 Focus Areas for Decarbonization

1. Low-Carbon Material Alternatives

Low-carbon materials, such as bio-based plastics and recycled inputs, reduce the carbon footprint of production and disposal. Bio-based plastics, derived from renewable sources like sugarcane or corn, emit up to 70% less CO_2 than fossil-based plastics, according to IPCC reports. In India, companies like Bio Prime produce bio-plastics from agricultural waste, supporting circularity by repurposing biomass.

Strategies:

- **Incentivize Adoption**: MoEFCC can offer subsidies for manufacturers switching to bio-based or recycled materials, targeting a 20% adoption rate by 2030.
- **Scale Recycling Infrastructure**: Invest in MRFs to recover plastics, metals, and textiles. The IPCC estimates that scaling recycling could reduce global waste sector emissions by 15–20%.
- **R&D Investment**: Fund research into biodegradable composites, leveraging India's biotech start-ups to innovate cost-competitive alternatives.

Case Study: Ecoware, an Indian start-up, produces compostable tableware from sugarcane bagasse, replacing singleuse plastics. Its products decompose within 90 days, reducing landfill methane emissions.

2. Energy Efficiency in Waste Processing Facilities

Waste processing facilities, including recycling plants and WTE units, are energy-intensive, contributing to 5% of global GHG emissions, per IPCC data. Energy efficiency measures can significantly lower this impact.

Strategies:

- **Technology Upgrades**: Replace outdated equipment with energy-efficient alternatives, such as high-efficiency motors and automated sorting systems. These upgrades can reduce energy use by 25%, as noted in MoEFCC's waste management guidelines.
- **Process Optimization**: Adopt anaerobic digestion for organic waste, which produces biogas while minimizing energy inputs. Facilities like Delhi's Okhla WTE plant demonstrate this approach, generating 24 MW of power from 2,000 tons of waste daily.
- **Monitoring Systems**: Deploy IoT sensors to track energy consumption in real time, enabling data-driven optimization.

Case Study: Saahas Zero Waste in Bengaluru retrofitted its recycling facility with energy-efficient conveyors and solar panels, cutting energy costs by 30% and emissions by 200 tons of CO_2 annually.

3. Electrification of Waste Collection Fleets

Waste collection vehicles, typically diesel-powered, contribute significantly to urban air pollution and GHG emissions. Electrifying these fleets aligns with India's EV30@30 campaign, aiming for 30% EV penetration by 2030.

Strategies:

- **Pilot Programs**: Municipalities can partner with EV manufacturers like Tata Motors to deploy electric waste collection trucks. Pilot projects in Pune have shown a 50% reduction in fuel costs.
- **Charging Infrastructure**: Develop solar-powered charging stations to ensure zero-emission operations. MoEFCC's FAME-II scheme provides subsidies for EV infrastructure.
- **Public-Private Partnerships (PPPs)**: Collaborate with private fleet operators to share costs and risks. For example, Hyderabad's PPP model has electrified 20% of its waste collection fleet since 2023.

Challenges: High upfront costs and limited charging infrastructure pose barriers. Solutions include leasing models for EVs and government-backed loans for municipalities.

4. Incorporating India's Renewable Energy Goals into Waste-to-Energy Projects

India's ambitious target of 500 GW of renewable energy capacity by 2030, as outlined by MoEFCC, provides a foundation for decarbonizing WTE projects. WTE facilities convert non-recyclable waste into electricity or heat, reducing landfill emissions and fossil fuel dependency.

Strategies:

- **Biogas Expansion**: Scale anaerobic digestion plants to process organic waste, producing biogas for power generation. India's 5,000+ biogas plants generate 10 MW annually, with potential for 10-fold growth by 2030.
- **Solar Integration**: Equip WTE facilities with rooftop solar panels to offset energy needs. The IPCC notes that hybrid renewable systems can reduce WTE emissions by 40%.
- **Policy Support**: Extend feed-in tariffs and carbon credits to WTE projects. MoEFCC's National Bioenergy Programme offers up to 50% capital subsidies for biogas plants.

Case Study: The Indore Municipal Corporation's WTE plant processes 1,000 tons of waste daily, generating 15 MW of renewable energy. Its integration with solar power has reduced its carbon footprint by 25% since 2024.

Decarbonization Strategies in Waste Management

Figure 24: Decarbonization strategies in WM

7.3 Implementation Considerations

Policy and Regulation:

- **Carbon Pricing**: Introduce a carbon tax on high-emission waste management practices to fund low-carbon alternatives, as recommended by the IPCC.
- **Extended Producer Responsibility**: Strengthen EPR regulations to hold manufacturers ac-

countable for end-of-life product management, encouraging low-carbon materials.

- **Subsidies and Incentives**: Expand MoEFCC's subsidies for renewable energy and EV adoption to include waste management innovations.

Financing:

- **Green Bonds**: Issue municipal green bonds to fund WTE and EV projects. India's green bond market grew to $20 billion in 2024, per MoEFCC data.
- **Blended Finance**: Combine public and private funds to de-risk investments in bio-based material start-ups and energy-efficient facilities.
- **Carbon Credits**: Streamline certification for WTE projects to access voluntary carbon markets, projected to reach $50 billion globally by 2030.

Stakeholder Engagement:

- **Industry Collaboration**: Partner with industry associations like FICCI to promote low-carbon materials and technologies.
- **Community Involvement**: Educate consumers on waste segregation to improve recycling efficiency, reducing energy use in processing.
- **Capacity Building**: Train MSME workers on energy-efficient practices and EV maintenance through NITI Aayog's skill development programs.
- **Strengthen Industry and Market Linkages:** Development of structured pathways for private sector participation by enhancing circular business systems that bridge the gap between producers, re-users, and end-users. This creates quality standards through green procurement policies and ensures economic scalability and viability. For example, encouraging FMCG companies to adopt recycled content targets in packaging and electronics manufacturers by implementing buy-back and refurbishing programs. This strengthens reverse supply chains and recycling infrastructure.

Integrating decarbonisation into the circular economy is critical for achieving India's climate goals and global sustainability targets. The proposed roadmap, focusing on low-carbon materials, energy-efficient waste processing, electrified fleets, and renewable energy-powered WTE projects, provides a clear path forward. By leveraging India's renewable energy ambitions, strengthening policy frameworks, and fostering stakeholder collaboration, the circular economy can become a cornerstone of low-carbon development. The strategies outlined align with IPCC recommendations and MoEFCC's vision, ensuring environmental and economic benefits for India and beyond.

7.4 Governance and Institutional Framework

Poor coordination between the central state and local bodies leads to hampered application and accountability gaps. For example, overlapping roles between CPCB, SPCBs, and ULBs can delay the decision-making and enforcement of waste management regulations. Effective implementation of a circular economy requires well-defined institutional roles, strong governance mechanisms, and robust accountability systems to ensure coordinated action across all levels.

Institutional Roles and Responsibilities

- **Central Government:** Constructs national policies, defines targets, and provides regulatory oversight and strategic guidance.
- **State Governments:** Adapt national policies to regional contexts, ensure enforcement, and offer capital support and infrastructure
- **Urban Local Bodies:** Implement decentralized waste management systems and deliver services at the local level.
- **Private Sector:** Foster investment, technology installation, and novelties in circular solutions.
- **Informal Sector:** Plays a critical role in collection, segregation, and recycling, and must be integrated into formal systems.

Governance Mechanisms

- The creation of a **National Circular Economy Mission** to aimed at providing strategic direction and coordination
- Establishing of **inter-agency collaboration platforms** to ensure policy alignment across sectors

- Implementation of **digital monitoring systems** for real time data tracking and informed decision-making

Accountability and Monitoring

- **Performance-based evaluation of** ULBs linked to service delivery outcomes
- **Monitoring compliance with the help of digital dashboards and reporting tools**
- **Enhance transparency and accountability through Third-party audits** and **public disclosure**

8 Stakeholder Engagement and Capacity Building

The success of a circular economy framework in India is deeply reliant on the engagement of a wide array of stakeholders, each playing a distinct yet interconnected role. Effective stakeholder engagement and capacity building are pivotal for achieving CE, addressing environmental, socio-economic, and governance challenges. From policy-making and urban governance to community participation and technological innovation, effective capacity building is crucial to ensure that CE principles are implemented consistently and sustainably across the country.

8.1 Stakeholder Mapping and Roles

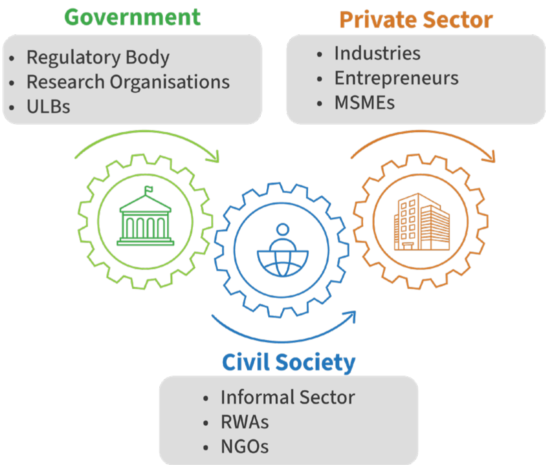


Figure 25: Roles of Stakeholders

Government Bodies

The transition to a circular economy in India requires coordinated efforts across multiple governance levels. The Central Government plays a pivotal role by formulating national policies, providing funding, and establishing regulatory frameworks that guide circular economy initiatives. State Governments are responsible for implementing state-specific strategies that align with national objectives while addressing region-specific waste management challenges. ULBs are key enablers on the ground, tasked with enforcing waste segregation, developing recycling infrastructure, and integrating circularity into urban planning. Cities like Indore and Panaji have pioneered decentralized waste systems through source segregation, localized composting, and continuous citizen engagement. These models are supported by regulatory guidance, digital tools, and scientific advisories provided by pollution control boards and affiliated environmental research institutes, which contribute to designing operational protocols and technical standards.

Private Sector

Industries and enterprises play a crucial role in advancing the circular economy. Large industries are expected to implement Extended Producer Responsibility (EPR) programs, design products with circularity in mind, and invest in robust recycling infrastructure. In Coimbatore and Hyderabad, producer-led reverse logistics systems for paper, plastics, and e-waste have emerged, integrating local recyclers and informal collectors. MSMEs can contribute by adopting resource-efficient practices and tapping into emerging business opportunities in waste recovery and recycling. Waste management companies support the ecosystem by offering professional services for the collection, segregation, and processing of diverse waste streams. Additionally, start-ups and innovators are driving technological advancements by developing solutions for waste tracking, efficient recycling, and creative upcycling methods.

In Hyderabad, producer-led reverse logistics systems - such as RLG India's 'E Safai' project - are integrating informal waste collectors into formal e-waste management through training and collaboration with local recyclers. Similarly, digital platforms like Recykal facilitate efficient reverse logistics for paper, plastics, and e-waste by connecting waste generators with authorized recyclers. (India's first DRS- Uttarakhand)

Civil Society

NGOs and environmental organizations play a vital role in promoting the circular economy by raising public awareness, advocating for policy reforms, and implementing community-based waste management projects. The informal waste sector, comprising waste pickers and recyclers, is essential to the recycling ecosystem and must be integrated into formal waste management systems to enhance efficiency and equity. Citizen groups and Resident Welfare Associations (RWAs) contribute at the grassroots level by encouraging household waste segregation and facilitating community composting initiatives. Academic and research institutions further support the circular economy by conducting in-depth research, developing innovative solutions, and offering technical expertise for policy and program implementation.

In urban areas like Mysuru, Thiruvananthapuram, and Surat, citizen-led initiatives supported by resident welfare associations have led to improved household segregation, composting, and plastic reduction.

8.2 Integration of Informal Waste Sector

India's vast informal sector, which manages a significant share of material recovery, particularly plastic and e-waste forms a cornerstone of the circular economy. The informal sector workers in waste management have historically remained unrecognized, despite their substantial contributions. With over 4 million informal waste collectors accounting for nearly 90% of the country's plastic recycling (NITI, 2021), there is a critical need to formalize their roles. Formal integration would not only acknowledge their contributions but also enhance their livelihoods by improving income security, providing social protection, and ensuring safer working conditions.

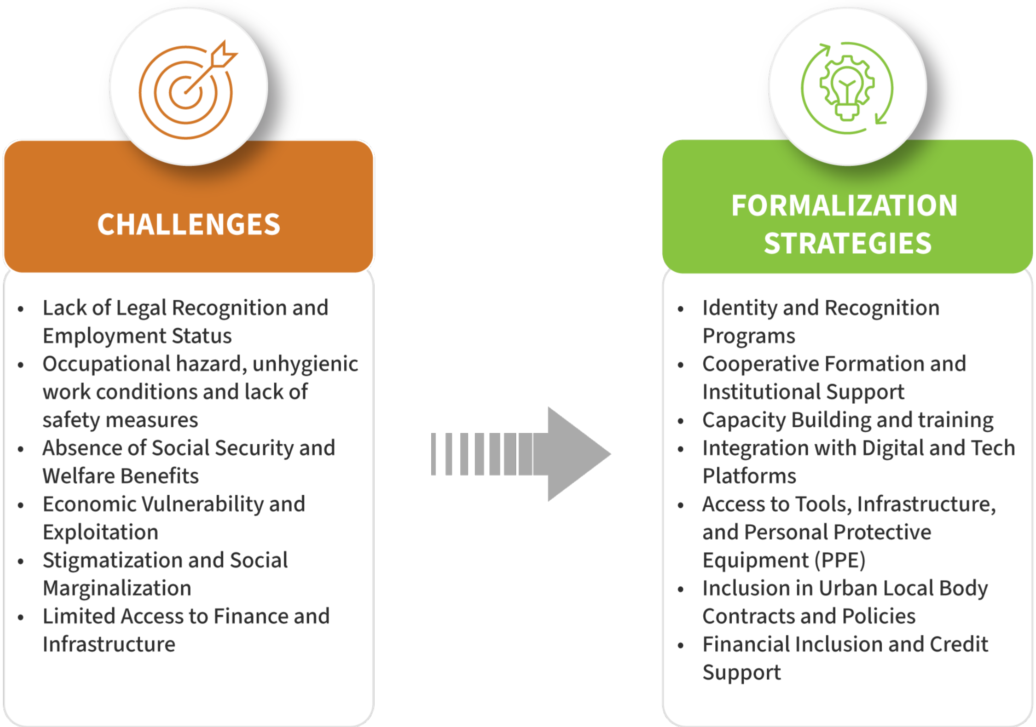


Figure 26: Challenges and Formalization Strategies of Stakeholder Engagement

SUCCESS STORIES

Hasiru Dala, Bengaluru

Hasiru Dala, a Bengaluru-based organization formally established in 2013, has integrated over 7,500 informal waste pickers into the formal waste management system through ID cards and municipal contracts. By securing social security, access to education, and recognition as "green workers," Hasiru Dala has empowered waste pickers across 18 cities to become professional service providers and key stakeholders in India's evolving solid waste landscape.

Source: *https://www.ndtv.com/video/hasiru-dala-a-bengaluru-based-ngo-that-works-to-empower-waste-pickers-728232*

SWACH cooperative Pune

SWACH Pune is India's first cooperative fully owned by self-employed waste pickers, with over 3,600 members serving 8.5 lakh+ properties daily. By integrating informal waste workers into a formal, transparent system, SWaCH has significantly improved their livelihoods, income, and dignity, handling 1,400 MT of waste per day with 95% segregation efficiency.

Source: *https://w.ndtvimg.com/sites/3/2019/08/14202540/650_10.jpg*

8.3 Capacity Building Programs

Several capacity-building initiatives for the informal sector have been developed through collaborations between NGOs and government agencies. Training modules on segregation techniques, occupational safety, and use of digital collection tools have improved the efficiency and safety of this workforce.

Technical Training

To enhance the effectiveness and sustainability of waste management systems, it is essential to institutionalize technical training programs for all stakeholders, particularly municipal workers and informal waste collectors. These programs should include structured training modules on scientific waste segregation and processing, ensuring adherence to health, safety, and environmental standards. Additionally, skill development in operating equipment such as composting units, recycling machinery, and material recovery facilities can significantly improve processing efficiency. As digital solutions increasingly become part of waste governance, digital literacy training must also be provided - enabling workers to use waste tracking applications, access digital payment systems, and participate in online marketplaces for recyclables. These capacity-building initiatives can professionalize the workforce, promote accountability, and support the formal integration of the informal sector into a modern circular economy framework.

Knowledge Enhancement

Knowledge-building interventions must target decision-makers and key influencers in the waste ecosystem. Educational programs on circular economy principles should be introduced across administrative and industrial sectors to promote long-term thinking and sustainable material use. Further, regulatory training is essential for compliance officers and environmental enforcement bodies to improve understanding of national laws and ensure consistent application of policies. To support innovation and policy alignment, international exchange programs with countries like the Netherlands and Denmark should be established - facilitating peer learning on systems such as urban mining, product stewardship, and circular design practices. Such initiatives will build institutional capacity and align local frameworks with global sustainability standards.

Target Groups and Approaches

Policy delivery should be customized to the needs of different stakeholders. For government officials, practical workshops on policy enforcement, monitoring tools, and cross-agency coordination can bridge the gap between regulation and on-ground outcomes. Industry professionals should receive technical training on eco-design, supply chain optimization, and EPR compliance to align their operations with circular economy goals. Informal waste workers, who play a crucial role in resource recovery, need targeted support through skill upgradation programs and business development assistance to help transition into formal systems and entrepreneurial roles. Lastly, community engagement strategies - such as door-to-door outreach, school-based initiatives, and media campaigns - should be used to promote sustainable consumption habits and household-level waste segregation, making citizens active participants in the circular economy.

Capacity Building

Figure 27: Capacity Building Programmes

8.4 Digital Collaboration Platforms

In today's rapidly evolving waste management ecosystem, a robust digital collaboration platform can act as a backbone for inclusive and efficient circular economy operations.

Proposed National Digital Platform Features

- **Multi-stakeholder Interface**: Customized dashboards for waste generators, collectors, processors, and regulators
- **Waste Exchange Marketplace**: Platform connecting waste generators with potential buyers of recyclable materials
- **Knowledge Repository**: Best practices, training materials, and success stories accessible to all stakeholders
- **Grievance Redressal System**: Mechanism for addressing issues and ensuring accountability

Benefits for Stakeholder Engagement

- **Transparency and Trust**: Real time tracking of waste movement builds trust among stakeholders
- **Data-Driven Decision Making**: Analytics help identify bottlenecks and optimization opportunities
- **Collaborative Governance**: Platform enables participatory decision-making and inclusive policy development
- **Economic Opportunities**: Creates markets for recyclable materials and circular products

8.5 Case Studies: Successful Stakeholder Engagement Models

Indore's Citizen Engagement Success

Indore's remarkable transformation into India's cleanest city is a powerful example of how multi-stakeholder engagement can drive systemic urban change. Since 2016, the Indore Municipal Corporation (IMC) has led a collaborative effort involving government authorities, NGOs, private enterprises, and active citizen participation to overhaul its waste management practices. Through public campaigns, neighborhood engagement, and consistent outreach, citizens embraced practices like 100% household waste segregation and supported the elimination of open garbage dumps. NGOs such as Sarthak and Basix played a pivotal role in integrating informal waste workers and running decentralized composting operations, while private contractors managed waste logistics and processing. Political will, coupled with administrative efficiency, ensured the city invested in infrastructure like transfer stations and waste-to-compost facilities, while implementing strict monitoring and accountability

measures. Community-driven initiatives, like waste audits in commercial zones and citizen-led market cleanliness drives, reinforced the sense of ownership. This collective approach - where every stakeholder from policymakers to street vendors contributed - has positioned Indore as a national model for inclusive and sustainable urban waste management.

Alappuzha's Decentralized Waste Management

Alappuzha, Kerala - also known as Alleppey - is globally recognized for pioneering a community-led decentralized waste management model under the initiative "Nirmala Bhavanam Nirmala Nagaram" (Clean Homes, Clean City). With 100% household coverage and scientific disposal, the city has eliminated landfilling and open dumping by fostering strong political will, public awareness campaigns, and local capacity building. Alappuzha's approach demonstrates the power of bottom-up planning, community ownership in creating sustainable, inclusive waste systems.

Ambikapur's Women-led Municipal Solid Waste Management

Ambikapur in Chhattisgarh exemplifies how gender-inclusive models can revolutionize waste management. Here, 447 women from marginalized backgrounds were organized into Self-Help Groups (SHGs) and entrusted with complete waste collection and processing responsibilities across the city. This decentralized model not only achieved 100% door-to-door waste collection but also generated an impressive ₹15 lakh in monthly revenue through resource recovery. The initiative empowered women economically and socially, turning them into respected environmental service providers. Ambikapur's story emphasizes the potential of combining livelihood creation with environmental governance.

Table 3: Stakeholder Capacity & Action Plan

Stakeholder	Capacity Needs	Suggested Actions
Informal Sector	Technical training, legal identity	Registration, skilling, and financial inclusion
ULBs & Officials	Digital literacy, CE frameworks	Workshops, manuals, model SOPs
Industries	EPR compliance, CE strategy	Guidance documents, digital audits
Citizens	Awareness of CE practices	Campaigns, school curriculum, and gamification apps

9 Monitoring and Evaluation Framework

An effective Monitoring and Evaluation framework is vital for assessing the impact and progress of circular economy initiatives. It helps track whether interventions are achieving their intended outcomes and provides the evidence necessary for course correction, replication, and scaling. This section outlines key metrics, the role of digital and AI-driven tools, and implementation recommendations to strengthen India's circular economy monitoring landscape.

9.1 Metrics for Assessing Progress

Tracking tangible indicators is essential for gauging the effectiveness of circular interventions. The following metrics provide a foundation for measuring progress:

- **Recycling Rate:** Measures the percentage of total waste that is recycled and reintegrated into production cycles.
- **Resource Recovery Rate:** Quantifies the amount of materials reclaimed from waste, such as metals, plastics, and organics.
- **Waste Diversion Rate:** Indicates the proportion of waste diverted from landfills and incineration to alternative channels such as composting and reuse.
- **Collection Efficiency:** Tracks the percentage of waste collected in relation to total waste generated, broken down by wet, dry, and hazardous categories.
- **Public Participation Rate:** Assesses the level of citizen involvement in segregation at source and adoption of sustainable consumption behaviours.
- These indicators should be standardized across municipalities and integrated into urban and rural waste management performance reports.

9.2 Metrics for Decarbonization

As circular economy practices aim to minimize environmental impact, decarbonization metrics are equally important:

- **GHG Emissions Avoided:** Calculates tons of carbon dioxide equivalent (tCO2e) avoided per ton of waste recycled, reused, or composted.
- **Energy Savings:** Measures the amount of energy conserved through recycling and resource efficiency initiatives.
- **Carbon Intensity by Treatment Method:** Compares the carbon footprint of various waste treatment pathways such as landfilling, incineration, composting, and recycling.
- **Use of Renewable Energy:** Tracks the share of renewable energy used in circular economy infrastructure such as MRFs and Waste-to-Energy (WtE) plants.

Such metrics should be aligned with India's climate

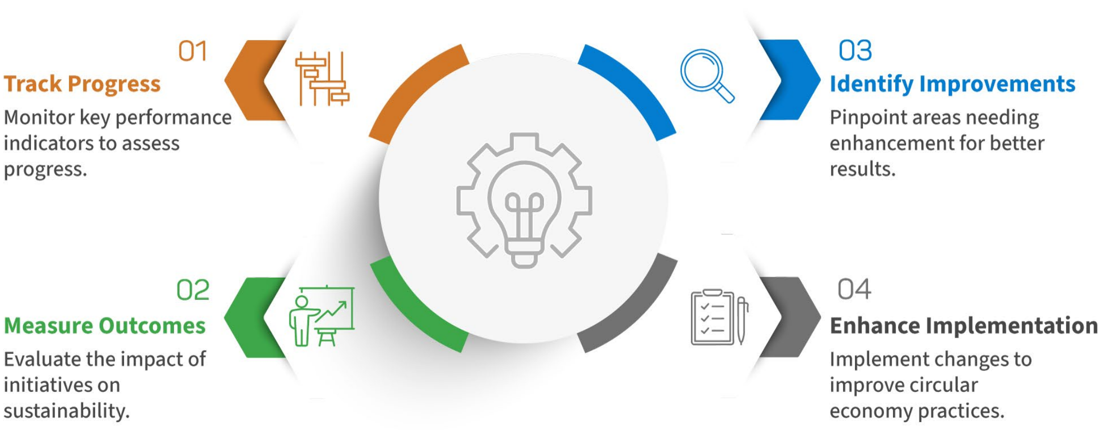


Figure 28: Monitoring and Evaluation Frameworks

goals under the Paris Agreement and integrated into environmental reporting frameworks.

9.3 Role of Digital Platforms in Monitoring

Digital platforms provide a backbone for real time data aggregation, compliance monitoring, and participatory governance. Their integration into M&E frameworks can significantly enhance transparency and accountability.

- **Centralized Data Systems:** National and state platforms can consolidate data from local bodies, industries, and informal actors, enabling integrated performance tracking.
- **Compliance Dashboards:** Regulators can monitor adherence to norms such as EPR, segregation mandates, and hazardous waste protocols.
- **Citizen Portals:** Public interfaces for feedback, reporting violations, and tracking municipal performance encourage community engagement.
- **Predictive Analytics:** Advanced data tools can forecast trends in waste generation and resource demand, aiding better infrastructure planning.

The Swachh Bharat Mission's real time dashboards and Smart Cities' digital command centers offer replicable models for other regions.

Integration of AI Tools for Real time Reporting

Artificial Intelligence can revolutionize the speed and accuracy of monitoring in circular systems. Applications include:

- **Computer Vision:** AI-powered cameras can detect illegal dumping or contamination in waste streams.
- **IoT Integration:** Smart bins equipped with sensors relay real time data on fill levels, triggering efficient waste collection routes.
- **Anomaly Detection:** AI can flag inconsistencies in waste generation or diversion patterns, prompting audits or interventions.
- **Sentiment Analysis:** Natural Language Processing tools analyze feedback from citizens and social media to gauge public satisfaction and identify gaps.

AI tools should complement human oversight and be deployed in a phased manner, prioritizing high-waste urban clusters.

9.4 Stakeholder-Centric Reporting and Governance

Effective M&E must reflect the needs of all stakeholders - from local governments to civil society:

- **Role-Based Dashboards:** Customized interfaces for policymakers, sanitation workers, industry players, and citizens.
- **Annual Circular Economy Scorecards:** Public reporting of city and state performance on circular metrics fosters healthy competition and accountability.
- **Incentive Mapping:** Linking performance indicators to financial incentives or policy relaxations can motivate better compliance.

Data Governance and Security

With the proliferation of digital data, robust data governance is essential:

- **Standardized Protocols:** Uniform data formats and reporting structures improve comparability and integration.
- **Privacy Safeguards:** Systems must ensure confidentiality of personal and commercially sensitive information.
- **Audit Trails:** Maintaining a digital record of data entries and edits ensures integrity and traceability.

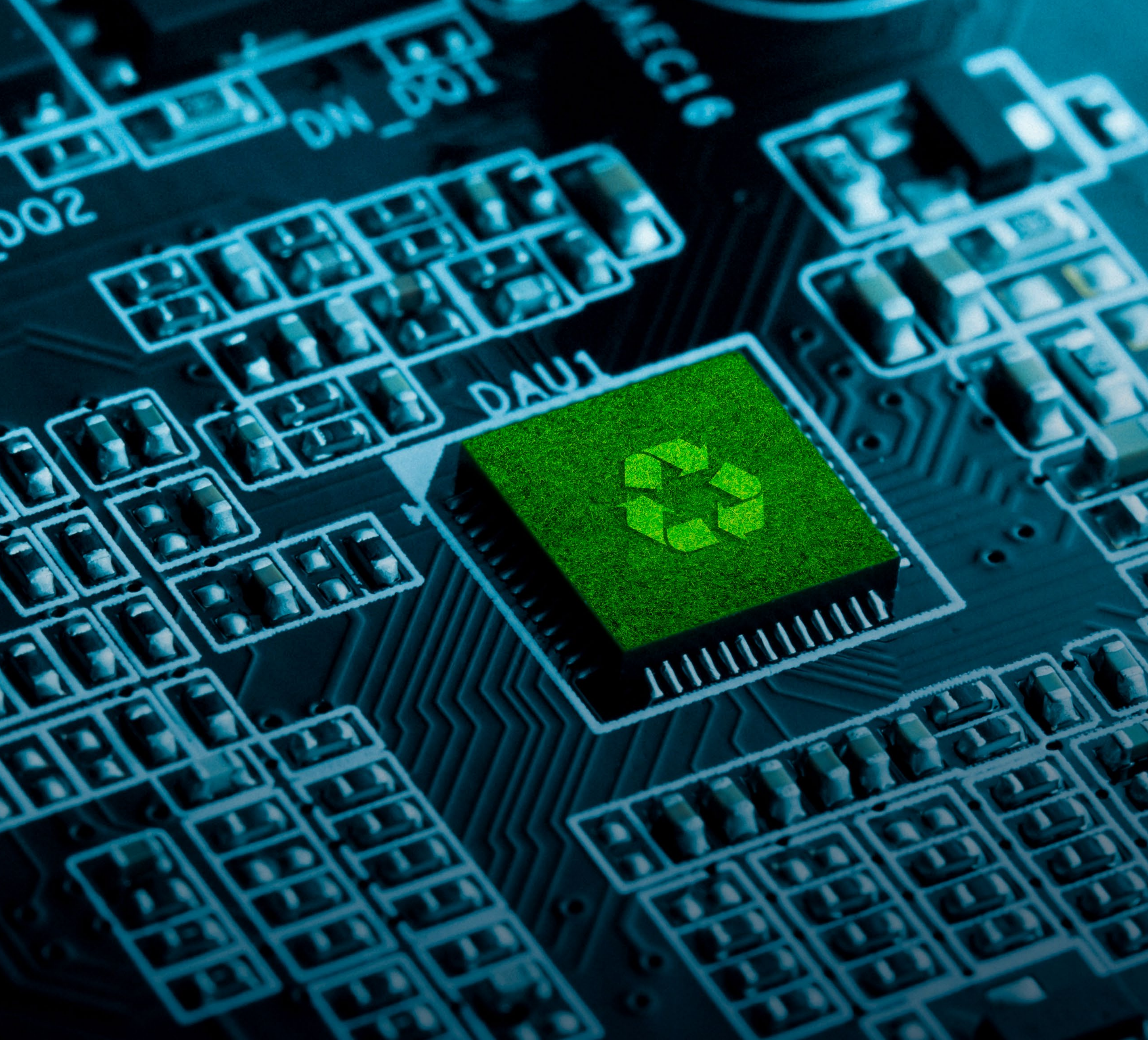
National and state governments should work together to create regulatory frameworks for data security and ethical AI use.

9.5 Recommendations for Implementation

- Institutionalize a national circular economy monitoring authority for standard setting and oversight.
- Build digital capacity at the ULB level to ensure accurate and timely data entry.

- Mandate integration of circular economy metrics into State of Environment Reports and Smart City performance indices.
- Encourage public-private partnerships for deploying AI and IoT tools in waste and resource tracking.

By building a transparent, data-driven, and inclusive monitoring system, India can ensure that its transition to a circular economy remains on track, scalable, and environmentally sound.



10 Challenges and Barriers in the Circular Economy

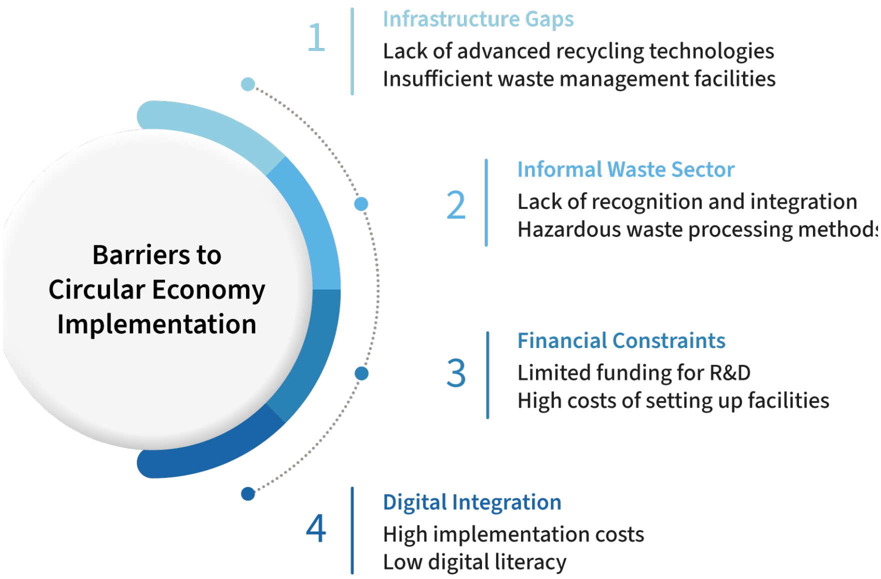


Figure 29: Challenges and Barriers in Circular Economy

The circular economy is a sustainable model that aims to minimize waste and maximize resource efficiency by promoting reuse, recycling, and the reduction of materials. In India, the adoption of CE principles is crucial given the country's rapid industrialization and environmental challenges. However, several barriers hinder the effective implementation of CE practices. This section explores the challenges and barriers to the circular economy in India, focusing on infrastructure gaps, financial constraints, the role of the informal waste sector, and the integration of digital platforms with on-ground practices.

10.1 Infrastructure Gaps

One of the most significant impediments to implementing CE in India is the lack of adequate waste management infrastructure, particularly in urban areas where waste generation is escalating due to population growth and consumerism. India's urban centres produce approximately 68.8 million tons of municipal solid waste annually, yet the infrastructure for waste segregation, collection, and recycling remains underdeveloped (CPCB, 2023). Many cities lack modern waste segregation facilities at the source, leading to mixed waste streams that complicate recycling efforts and result in inefficient resource recovery (Selvaraj et al., 2024, Pati & Agrawal, 2024). For example, only about 30% of collected waste in India is processed through recycling or composting, with the remainder often ending up in landfills or open dumpsites, contributing to environmental degradation (Kapse et al., 2024).

Furthermore, the limited availability of advanced recycling technologies, such as automated sorting systems or waste-to-energy plants, hinders the scalability of CE initiatives. Waste-to-energy plants, which could convert non-recyclable waste into energy, are scarce, with only a few operational facilities in cities like Delhi and Hyderabad (Bhatia et al., 2024). The absence of integrated municipal solid waste management (ISWM) systems exacerbates these issues, as many municipalities still rely on outdated practices focused on waste disposal rather than resource recovery. For instance, open burning of waste and unregulated landfilling remains common in smaller towns and cities, undermining CE goals and contributing to air and soil pollution (Kapse et al., 2024).

To address these infrastructure gaps, India needs significant investments in modern waste management facilities, including MRFs, composting plants, and waste-to-energy infrastructure. PPPs could play a pivotal role in bridging this gap by mobilizing private sector expertise and funding. Additionally, ULBs should prioritize source segregation through awareness campaigns and incentivize the adoption of decentralized waste management systems to reduce the burden on centralized facilities.

10.2 Financial Constraints

Financial constraints pose a formidable barrier to the adoption of CE practices in India. Establishing and maintaining the infrastructure required for a circular economy, such as recycling plants, waste-to-energy facilities, and advanced material processing units, involves substantial capital expenditure. For instance, setting up a single waste-to-energy plant can cost upwards of ₹100 crore (approximately $12 million USD), which is often beyond the financial capacity of many municipalities, particularly in smaller cities and towns (Sheth, 2024). Moreover, the operational costs of maintaining such facilities, including labour, energy, and maintenance, add to the financial burden (Dutta et al., 2023).

Research and development (R&D) in circular technologies also suffers from limited funding. Innovations in areas such as biodegradable materials, advanced recycling techniques, and waste-to-resource technologies require significant investment, yet public and private sector funding for such initiatives remains inadequate (Pati & Agrawal, 2024). This lack of investment stifles innovation and limits the scalability of CE practices, particularly in sectors like textiles, plastics, and electronics, which are critical for circularity.

The informal waste sector, which handles a significant portion of India's waste, also faces financial challenges. Informal workers, including waste pickers and small-scale recyclers, often operate on razor-thin margins and lack access to formal financing mechanisms such as bank loans or microfinance. Without financial support, these workers are unable to invest in safer equipment or more efficient technologies, perpetuating low productivity and hazardous working conditions.

To overcome these financial barriers, innovative financing models are essential. Green bonds, impact investing, and subsidies for CE-focused enterprises could provide the necessary capital. Additionally, government schemes like the Swachh Bharat Mission could allocate dedicated funds for CE infrastructure and R&D. For the informal sector, microfinance institutions and cooperatives could offer tailored financial products to support small-scale waste management enterprises, enabling them to adopt sustainable practices and integrate into the formal economy.

10.3 Role of the Informal Waste Sector

The informal waste sector is a cornerstone of India's waste management system, employing an estimated 1.5–4 million waste pickers who handle a significant portion of the country's recyclable waste (Tiwari et al., 2023). These workers play a crucial role in resource recovery, diverting materials such as plastics, metals, and paper from landfills to recycling streams. However, their contribution to CE is hindered by systemic challenges, including lack of formal recognition, inadequate working conditions, and limited access to technology and training.

Informal waste workers often operate outside formal systems, without legal protections, social security, or access to healthcare. This lack of recognition marginalizes them and limits their ability to contribute effectively to CE goals. For example, waste pickers are frequently excluded from municipal waste management contracts, which prioritize formal organizations, leaving informal workers to compete for scraps in hazardous conditions.

Moreover, the informal sector's reliance on rudimentary and unsafe methods, such as acid leaching or burning to extract materials from e-waste, poses significant health and environmental risks. For instance, informal e-waste recycling in areas like Seelampur in Delhi has been linked to soil and water contamination, as well as health issues like respiratory problems among workers (George & Cekuls, 2024; Panigrahi et al., 2021). These practices not only undermine CE objectives but also perpetuate social inequities.

Formalizing the informal waste sector is critical to enhancing its role in CE. This could involve registering waste pickers and recyclers under cooperatives or self-help groups, providing them with identity cards, protective equipment, and access to training programs on safe and efficient recycling techniques. Partnerships between municipalities, NGOs, and private companies could facilitate the integration of informal workers into

Challenge	Description	Citation
Infrastructure Gaps	Lack of adequate waste management infrastructure and advanced recycling technologies.	(Selvaraj et al., 2024.) (Pati & Agrawal, 2024)
Financial Constraints	High costs of setting up recycling facilities and a lack of funding for R&D.	(Sheth, 2024) (Dutta et al., 2023)
Informal Waste Sector Issues	Lack of recognition, regulation, and access to better technologies for informal workers.	(Kala & Bolia, 2024) (Tiwari et al., 2023)
Digital Platform Integration	Limited digital literacy and infrastructure to support digital solutions.	(Yadav et al., 2021) (Amaleshwari & Jeevitha, 2023)
Public Participation & Consumption	A regulatory effort is needed to make the transition from single-use disposables to reusable ones. Also, awareness of the enforcement issues, the need for sustained behavioral change among citizens, and non-compliance with SWM regulations should be induced among the citizens.	Report on Brainstorming discussion on building circular economy solutions for Bengaluru city – IISC, Bangalore, 2025

Table 4: Key Challenges and Barriers to the Circular Economy in India

formal waste management systems. For example, initiatives like the "Kabadiwalla Connect" project in Chennai have successfully linked informal recyclers with formal systems, improving their income and working conditions while boosting recycling rates (Krishnan, 2023). Scaling such models nationwide could significantly advance CE in India.

10.4 Integration of Digital Platforms with On-Ground Practices

Digital technologies, including AI, the IoT, blockchain, and data analytics, hold immense potential to transform waste management and advance CE practices in India. AI-powered systems can optimize waste collection routes, reducing fuel consumption and operational costs, while IoT-enabled smart bins can monitor waste levels in real time, improving collection efficiency (Kumar, 2024). Blockchain technology can enhance transparency in the recycling supply chain, ensuring traceability of materials and fair compensation for stakeholders (Mondal et al., 2023). Additionally, digital platforms like mobile apps can connect waste generators with recyclers, creating a marketplace for reusable materials (Amaleshwari & Jeevitha, 2023).

Despite this potential, integrating digital platforms with on-ground practices faces significant challenges. A key issue is the lack of digital literacy among waste management stakeholders, particularly in rural areas and the informal sector.

Many waste pickers and small-scale recyclers lack access to smartphones or the skills to use digital tools, limiting their ability to engage with technology-driven solutions (Yadav et al., 2021). Additionally, the high costs of implementing digital infrastructure, such as IoT sensors or cloud-based platforms, pose a barrier for cash-strapped municipalities and small businesses (Dutta et al., 2023).

Infrastructure challenges, such as unreliable internet connectivity and power supply in rural and semi-urban areas, further hinder the adoption of digital solutions. For instance, a smart waste management system relying on IoT requires consistent connectivity, which is often unavailable in smaller towns (Amaleshwari & Jeevitha, 2023). Moreover, the lack of interoperability between different digital platforms can create inefficiencies, as stakeholders may use incompatible systems that hinder seamless data sharing.

To address these challenges, targeted interventions are necessary. Digital literacy programs tailored for informal workers and small-scale recyclers could bridge the knowledge gap, while subsidies or low-cost financing could make digital tools more accessible.

Pilot projects, such as smart waste management systems in cities like Bengaluru and Pune, demonstrate the potential of digital integration and could be scaled with government support. Additionally, investments in rural internet infrastructure and public-private collaborations could ensure broader access to digital technologies, enabling their integration with on-ground CE practices.

The transition to a circular economy in India is fraught with challenges, including inadequate infrastructure, financial constraints, the marginalization of the informal waste sector, and barriers to digital integration. Addressing these issues requires a multifaceted approach, combining policy reforms, infrastructure investments, and targeted interventions to support informal workers and promote digital literacy. For instance, strengthening waste management infrastructure through PPPs, providing financial support for CE innovations, formalizing the informal sector, and scaling digital solutions can pave the way for a more sustainable and resource-efficient economy. By tackling these barriers, India can harness the potential of the circular economy to address its environmental challenges and promote sustainable development, aligning with global goals such as the United Nations' Sustainable Development Goals.

10.5 Risk Assessment and Mitigation Strategies

While the challenges associated with implementing a circular economy are well recognized, their effective management requires a structured and proactive risk mitigation approach. Key risks emerge from institutional limitations, fragmented governance structures, financial constraints, technological uncertainties, and socio-economic considerations. Addressing these risks is critical to ensure smooth, scalable, and inclusive implementation of circular economy interventions across India.

Key Risks and Mitigation Measures

1. Institutional Capacity Constraints: Many ULBs and implementing agencies face limitations in technical expertise, managerial capabilities, and operational efficiency, which can hinder the effective deployment of circular economy strategies.

- **Mitigation:** Strengthening institutional capacity through targeted training programs, development of standardized operational toolkits, and establishment of dedicated technical support units at state and regional levels can significantly enhance implementation efficiency. Partnerships with research institutions and knowledge organizations can further bridge capacity gaps.

2. Fragmented Governance and Coordination Challenges: The presence of multiple stakeholders across central, state, and local levels often leads to overlapping mandates, lack of clarity in roles, and weak coordination, resulting in inefficiencies in policy execution.

- **Mitigation:** Establishing formal inter-ministerial coordination mechanisms, nodal agencies, and unified policy frameworks can streamline decision-making. Digital governance platforms and integrated data systems can further enhance transparency, coordination, and accountability across institutions.

3. Technology Adoption and Scalability Risks: Advanced technologies such as AI-driven waste management systems, IoT-based monitoring, and resource recovery innovations often face challenges related to high costs, limited adaptability, and scalability across diverse urban contexts.

- **Mitigation:** Promoting pilot-based implementation, followed by phased scaling based on performance evaluation, can reduce risks. Encouraging indigenous innovation, localization of technologies, and collaboration with startups can improve adaptability and cost-effectiveness.

Social Risks and Informal Sector Displacement: A significant portion of India's waste management ecosystem is supported by the informal sector, whose livelihoods may be adversely impacted by formalized systems and technological interventions.

- **Mitigation**: Integrating informal workers into formal systems through recognition, skill development, financial inclusion, and social protection measures is essential. Inclusive policy frameworks that promote cooperatives, micro-enterprises, and fair market access can ensure equitable and just transition.

A robust circular economy transition is best demonstrated through successful, scalable case studies that offer replicable lessons across geographies. This section highlights prominent Indian and global examples where digital innovation, stakeholder coordination, and decarbonization have been effectively integrated into waste management systems.

11 Case Studies & Best Practices

11.1 A Glimpse of National Waste Management Practices

India's national waste management techniques are focused on minimizing, sorting, processing, and safely disposing of various waste streams using a combination of centralized and decentralized systems supported by regulatory frameworks. For municipal solid waste processing, the Municipal Solid Waste Management Rules, 2016 serve as the foundation, requiring scientific treatment, source segregation (hazardous, dry, and wet), and door-to-door collection.

Scientific disposal, public involvement, and the transition from a collect–transport–dump system to a segregate–process–recover–dispose paradigm are further fueled by national initiatives such as the Swachh Bharat Mission, National Green Tribunal (NGT) guidelines, and smart city projects.

Another example is Pune's SWaCH cooperative integrates waste pickers into the formal system, offering app-based complaint registration, monitoring, and payments. Bengaluru's Hasiru Dala platform not only registers waste workers for municipal contracts but also provides training, digital payment integration, and real time tracking. These efforts help in recognizing the informal sector's role in material recovery and empower them through digital inclusion.

These examples underscore the potential of blending community engagement, digital infrastructure, and circular economy principles to build resilient, inclusive, and sustainable waste management ecosystems. As India and the world work towards climate and sustainability targets, these models offer actionable insights to inform future policy and practice. Other examples for healthy waste management practices across India are given as follows:

AMBIKAPUR

A Swachhata Didi–Led Decentralized Waste Management

The Ambikapur Municipal Corporation began the Swachh Ambikapur project in June 2015, which has revolutionized municipal garbage management. This municipal success story rests on the shoulders of self-help groups composed of women from marginalized communities. These groups collect and segregate waste from all 48 municipal wards, achieving 100% door-to-door coverage. The recyclable materials are sold, and the system generates Rs. 15 lakhs in monthly revenue. Ambikapur's decentralized model, enhanced by women's leadership, combines social empowerment with effective urban sanitation.

Source: *Pandey, K. (2023). Ambikapur's women-led waste management system also generates revenue for the city. Mongabay-India.*
Source: *Pandey, K. (2023). Ambikapur's women-led waste management system also generates revenue for the city. Mongabay-India.*

INDORE

A Model of Integrated Urban Waste Management

Indore's transformation into India's cleanest city reflects the power of a multi-stakeholder approach backed by political will, citizen engagement, and effective digital integration. The city achieved 100% door-to-door collection and household waste segregation across all wards. Waste is processed using decentralized and centralized systems, producing compost and fuel. Private companies and NGOs (such as Basix and Sarthak) have helped integrate informal workers. Indore's waste tracking system, supported by a centralized digital dashboard, enables real time monitoring of waste flow, operational efficiency, and compliance. Its landfill reclamation and resource recovery have made it a flagship Indian example of a circular and low-emissions urban waste system

Source: https://imcindore.mp.gov.in/_next/image?url=https%3A%2F%2Fimcindore.mp.gov.in%2Fuploads%2FUntitled_design_15_9a346b39e3.jpg&w=1920&q=75
&
https://earth5r.org/wp-content/uploads/2024/03/Indore-Waste-Management-Earth5R-Environmental-organisation-app-1230x767-1-1024x639.webp

ALAPPUZHA, KERALA

Decentralized, Zero-Waste Innovation

Alappuzha's Clean Homes Clean City initiative, launched in 2012, emphasizes community-driven, decentralized waste management. With over 80% of households having biogas plants or composting units, the city has dramatically reduced its waste sent to landfill. The model operates without centralized waste collection, empowering citizens to manage wet waste at the source. The UNEP-recognized success of this approach underlines the effectiveness of lsow-tech, high-engagement strategies in small cities.

Source:
https://southasia.iclei.org/wp-content/uploads/2024/05/image_2024_03_19T05_24_40_316Z.png &
https://i0.wp.com/vikalpsangam.org/wpcontent/
uploads/migrate/Settlements/richaagarwalalappuzha1wastem.jpg?w=1024&ssl=1

11.2 Waste Management Practices on a global scale

Waste management techniques differ greatly throughout Asia. Modern systems with precise segregation, high recycling rates, and effective energy recovery methods are shown by high-income nations like South Korea and Singapore. In between, developing nations like the Philippines, Indonesia, and India are steadily moving away from dependence on landfills and toward community-driven solutions, recycling, and segregation. In order to achieve their sustainability goals, nations in the Middle East, like the United Arab Emirates, Saudi Arabia, and Qatar, are making big investments in recycling facilities, waste-to-energy plants, and smart management. More community involvement, stronger regulations, and circular economy techniques to reduce waste and environmental damage are generally the trends in the region. Few examples from developed nations are as follows:

1. Japan: Waste Management through the 3R Approach

Japan's waste management system is one of the world's most efficient, thanks to meticulous segregation, innovative technology, and widespread public involvement. Waste is carefully divided into categories such as flammable, non-flammable, and recyclable, along with strict handling guidelines. More than 70% of municipal waste is burnt in modern energy-generating plants, whereas landfills are only used for residues. The nation enforces the 3Rs (Reduce, Reuse, Recycle) and holds manufacturers accountable for recycling devices and appliances. Japan has built a sustainable model of waste management through disciplined citizens, eco-friendly regulations, and innovative waste-to-energy technologies, despite challenges such as high costs and rising plastic waste.

2. The Netherlands: Circular Economy Coalition and EPR Integration

The Dutch government has set national targets to transition key sectors to circularity by 2050. Their model integrates extended producer responsibility (EPR), sectoral transition teams (including government, academia, civil society, and industry), and real time material flow data systems. In waste management, the Netherlands diverts over 80% of its municipal solid waste from landfills, using advanced sorting, reuse, and recycling infrastructures. Digital material passports for buildings and electronics ensure traceability and accountability across the supply chain.

3. Denmark: Local Government Leadership and Resource Recovery

Denmark's decentralized approach involves municipalities in designing and implementing circular initiatives. Copenhagen, for instance, mandates waste separation at source for organic, plastic, paper, and hazardous waste. Denmark's incineration infrastructure, with energy recovery, reduces landfill dependency to below 2%. Combined with strict regulations and public engagement, Danish waste systems exemplify the synergy of environmental and energy policies.

4. Sweden: Waste-to-Energy and Emissions Mitigation

Sweden recycles nearly 50% of its waste and converts the rest into energy through incineration, supplying district heating and electricity. With over 30 waste-to-energy plants, the country imports waste to keep them running. Modern facilities are equipped with scrubbers and filters to control emissions. Sweden's approach, while debated, has helped offset fossil fuel use and reduce landfill emissions, illustrating how waste management can directly contribute to national decarbonization goals.

5. China: Smart Waste Management and AI Adoption

China's urban centers like Shanghai and Shenzhen have adopted AI-based waste segregation bins and mobile apps that guide citizens on sorting rules. The social credit system in some areas even incorporates waste compliance as a behavioral metric. Pilot programs use drones and sensors to monitor landfill emissions. Digital reporting tools and real time dashboards allow municipalities to track recycling performance and emissions, aligning with China's broader carbon neutrality commitments.

These examples underscore the potential of blending community engagement, digital infrastructure, and circular economy principles to build resilient, inclusive, sustainable waste management ecosystems. As India and the world work towards and sustainability targets, these models offer actionable insights to inform future policy and practice.

6. Brazil: Insights from a 1.3% Circular Economy Baseline

Brazil's noteworthy achievement is reaching a 1.3% circular economy baseline, which means that nearly all of the materials used are produced from virgin sources instead of being recycled or reused. This demonstrates a great dependence on natural resources, particularly biomass, which is widely consumed across the country. Brazil extracts more than 5.2 billion tonnes of materials each year, the majority of which are biomass and non-metallic minerals, and uses approximately 4.1 billion tonnes within its domestic economy.

Strengthening recycling infrastructure, sustainable agriculture methods, and novelties in waste treatment by including rag pickers in the framework are some key pathways to close the gap and increase circularity.

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India's waste holds untapped potential for material recovery, energy generation, and climate mitigation.

Closing the loop for a resource-efficient and sustainable future.

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