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Exploring Circular Economy Pathways for Biomedical Waste Management in India

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Abstract: *India's biomedical waste (BMW) generation is growing rapidly, driven by expanding healthcare infrastructure, rising population, and episodic surges (e.g., COVID-19). The dominant linear "take-make-dispose" approach for BMW treatment is encountering stress due to limited treatment capacity, regulatory gaps, and inefficient practices. A transition towards a circular economy (CE) paradigm—where waste is minimised, reused, recycled, recovered, and resources are kept in use longer—offers significant promise in the biomedical waste sector resulting in improved resource efficiency, reduced environmental impact, and new economic value streams. This paper presents a technical review of the current BMW landscape in India, examines circular economy models as applied to BMW, analyses opportunities and challenges (technical, regulatory, institutional, and behavioural) for implementation, and outlines roadmap for leveraging CE in India's BMW management.*
Keywords: *Biomedical Waste Management, India, Circular Economy*

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I. Introduction

Biomedical waste (BMW) is defined as waste generated during diagnosis, treatment or immunisation of humans or animals or in research activities, including categories such as sharps, pathological waste, microbiological waste, etc [1,6].

In India, the healthcare sector is expanding rapidly in terms of bed-capacity, diagnostics, testing, and ancillary services. This growth, alongside episodic surges (such as during the COVID-19 pandemic [7]) has led to increasing volumes of biomedical waste, putting pressure on collection, transportation, treatment and disposal infrastructure. Effective management of the huge volumes of BMW is critical due to its potential for infection spread, chemical and toxic exposure, and environmental contamination. India has been regulating BMW under the Bio-Medical Waste Management Rules, 2016 (BMWM Rules, 2016) and subsequent amendments [2]. But as volumes increase and complexities (such as single-use plastics in healthcare) mount, the dominant linear "take-make-dispose" approach for BMW management is encountering stress due to limited treatment capacity, regulatory gaps, and inefficient practice.

The circular economy (CE) concept, which aims to keep resources circulating by reducing waste, reusing, refurbishing, remanufacturing and recycling [8], offers an alternative paradigm. Applying CE to BMW could transform how healthcare systems, waste service providers and regulators view BMW: not solely as hazardous waste to be destroyed or disposed, but as a resource stream from which value (material recovery, energy, service-life extension) can be derived. Applying CE to BMWM offers the promise of converting "waste" into "resource", reducing landfill/incineration loads, recovering materials, energy and facilitating safer, more sustainable systems.

This paper explores the CE-pathways that might be applied to BMW in India, identifies the opportunities these pathways offer (resource recovery, material loops, energy recovery, design for waste minimisation), and examines the constraints inhibiting widespread uptake implementation in Indian context (regulatory, technical, financial, behavioural). Recommendations and roadmap for actionable implementation are also suggested.

II. Current Landscape of Biomedical Waste Management in India

India has been regulating BMW under the Bio-Medical Waste Management Rules, 2016 (BMWM Rules, 2016) and subsequent amendments [2]. In recent years, the increased usage of single-use items (masks, PPE, test kits) has resulted in large volumes and more complexity of the BMW generated in India. A 2018 ASSOCHAM-Velocity study [5] had projected BMW market growth at ~7% CAGR (2018-22) from 550.9 tons/day to ~775.5 tons/day by 2022. According to a recent study conducted by IMARC Group [9], the Indian medical waste management market is projected to reach USD 3.45 billion by 2033, growing at ~10% CAGR (2025-33).

2.1 Generation and Treatment Volumes

Available data show that India's BMW generation has grown and remained at high levels. According to the Asian Hospital monthly report (2024-25), the hospital generated ≈ 7,455 kg / month of BMW (≈247 kg/day) across categories [3]. At All India Institute of Medical Sciences (AIIMS) Raipur, ≈8914Kg/month of BMW was generated from Dec. 2024 to Sep. 2025 [4]. As per the Central Pollution Control Board (CPCB) report for 2022 [10], approx. ~705 tonnes/day BMW was generated, of which ~645 tonnes/day could be treated (≈ 91.5 %) using common biomedical waste treatment facilities (CBWTFs) and captive treatment. In 2023, ~859 tonnes/day generated, of which ~694 tonnes/day treated [11].

The above figures indicate both rising generation and a non-trivial untreated fraction. For instance, the gap between generated and untreated waste at national level has significantly risen from 8.5% in 2022 to 19.2% in 2023. The major challenge areas for BMW management include: lack of data, inadequate infrastructure, mixing of BMW with municipal waste, inadequate awareness/training of handlers.

2.2 Infrastructure and Treatment Facilities

As of 2023, there were 234 CBWTFs in India and 225 incinerators dedicated to BMW treatment [11].Treatment methods include incineration, autoclaving, microwaving, deep burial, plasma pyrolysis etc [10, 11]. As per the CPCB 2023 report [11], there are 4,35,257 healthcare facilities (HCFs) in India; of these, ~ 3,14,586 (≈72%) use CBWTFs; ~ 15,870 HCFs (~3.6%) have captive treatment; ~27.89% of HCFs neither use CBWTF nor captive treatment. Significant gaps remain in data completeness, authorisation of HCFs, proper segregation, and treatment capacity. For example, as per CPCB data, ~24,705 HCFs were operational without authorisation and incomplete installation of effluent treatment plants (ETPs) by bedded HCFs.

2.4 Key Challenges in Current Status

Some of the prominent hurdles faced in managing the BMW in India include [10, 11]:

- Segregation at source is often sub-optimal, leading to mixed waste streams, increased risk and costs.
- Treatment capacity, while growing, is unevenly distributed geographically; some states report large untreated fractions (e.g., Bihar, Karnataka) per CSE.
- Data gaps and monitoring weaknesses exist (unauthorised HCFs, treatment gaps).
- Episodic surges (e.g., COVID-19) create stress on the system.

III. Circular Economy Principles and Their Relevance to Biomedical Waste

3.1 Conceptualising Circular Economy in BMWM

A CE model emphasises moving away from the linear "take-make-dispose" framework to one in which resources are kept in use as long as feasible, maximum value is extracted while in use, and materials are recovered and regenerated at end of life. One typology uses the *9R* framework: Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover, Regenerate [8]. In the healthcare/BMW context, this may translate into:

- **Reduce**: Minimising waste generation (e.g., switching to reusable instead of single-use items where safe).
- **Reuse/Refurbish/Remanufacture**: Reconditioning certain devices or equipment instead of discarding.
- **Repurpose**: Transforming certain biomedical waste (after proper decontamination) into other useful materials.
- **Recycle**: Recovering plastics, metals from BMW streams (after safe segregation).
- **Recover**: Energy recovery from appropriate BMW fractions (e.g., certain non-infectious plastics).
- **Regenerate**: Enabling the healthcare waste-management system and materials flows to support ecosystem health (e.g., nutrient recovery, biogas).

In [8], it is observed that approximately 25 % of BMW is constituted by recyclable plastics, presenting a substantial resource potential.

3.2 Why CE is pertinent for BMW in India

Circular Economy (CE) principles are highly pertinent for biomedical waste (BMW) management in India due to the country's growing healthcare sector and the corresponding surge in waste generation [8]. Traditional linear disposal methods—collection, incineration, and landfilling—pose significant environmental and health risks, including air pollution, soil contamination, and pathogen spread. Rising volumes of BMW imply increasing disposal burdens, land use, emissions (from incineration) and costs — a linear disposal model may become unsustainable. Additionally, many biomedical devices and consumables include plastics, metals and other materials which have value if recovered and thus have an impact on resource scarcity and price volatility.

CE approaches promote resource recovery, waste minimization, and material reuse through segregation at source, sterilization, recycling of plastics and metals, and energy recovery from non-recyclable fractions. Implementing CE in BMW management not only aligns with India's Swachh Bharat initiative and Sustainable Development Goals (SDGs) but also enhances the efficiency and sustainability of healthcare waste systems by reducing landfill dependency, conserving resources, and lowering the carbon footprint of healthcare operations. Implementation of CE principles for BMW also presents economic opportunity as resource recovery improves the economics of treatment.

3.3 Quantitative Illustration of Circular Opportunity

While full quantitative modelling is beyond this paper, approximate estimation is presented below demonstrating the meaningful potential of circular economy scale.

- Suppose India treats ~645 t/day of BMW (2022); if 10% of that (≈64.5 t/day) is plastic/metal packaging that could be recovered, that equates to ~23,500 t/year of recoverable material.
- Energy recovery: if non-recyclable combustible fraction (~30% of treated BMW = ~193 t/day) is used for energy with a calorific value of 8 MJ/kg, the energy potential is ~1,540 MJ/day (~0.43 GWh/year).

IV. Opportunities for Circular Economy Pathways in BMW Management

BMW management presents a critical environmental and public health challenge, particularly in developing economies with expanding healthcare infrastructure such as India. Adopting CE pathways offers a transformative opportunity to reframe BMW management by emphasizing waste reduction, resource recovery, and material valorisation. Through innovations in waste segregation, safe material recycling, sterilization technologies, and energy recovery processes, CE strategies can help minimize environmental impacts while creating value from biomedical waste streams. These pathways not only enhance sustainability and compliance within the healthcare sector but also contribute to national goals for resource efficiency and a low-carbon economy. The plausible pathways for CE in BMW include:

1. *Material recovery & recycling*: 25 % of BMW is constituted by recyclable plastics, thus presenting a substantial resource potential [8]. Metals (e.g., needles, surgical instruments) can be cleaned/sanitised and returned for reuse or scrap value. Segregation at source is crucial. If BMW is appropriately segregated into infectious vs non-infectious, recyclable fractions can be harvested, reducing overall treatment cost and enabling circularity.
2. *Reusable and refurbished medical devices*: For bedded HCFs and non-bedded facilities, shifting from single-use to high-quality reusable items (where safe and feasible) reduces waste generation. Refurbishment of diagnostic equipment, surgical tools, and sharing repurposed devices across HCFs can bring down procurement burden and reduce waste streams.
3. *Energy recovery and resource regeneration*: Some BMW fractions, after safe treatment/sterilisation, may be used in waste-to-energy plants or for production of refuse-derived fuel (RDF). For example, incineration or pyrolysis of certain non-infectious plastic waste may recover energy, though care is needed with emissions. Biogas or composting (for non-hazardous biodegradable fractions) can regenerate resources (nutrients, energy) — though in BMW this is more limited.
4. *Supply-chain redesign and take-back models*: Device manufacturers or service providers may adopt take-back schemes for end-of-life (EOL) medical devices. Developing circular supply chains for healthcare consumables (sterile packaging, modular design) could enable reuse loops.
5. *Economic and policy incentives*: The BMW management market in India is expected to grow from USD 2.32 billion in 2024 to USD 3.53 billion by 2030 (CAGR ~7.11 %) [13]. Integration of CE may reduce net treatment costs and create new revenue streams (material recovery, refurbished equipment business). Policy frameworks encouraging Extended Producer Responsibility (EPR), resource recovery, green procurement in healthcare can accelerate CE pathways.

V. Constraints and Challenges to Implementing CE in BMWM in India

Implementing CE principles in BMW sector in India faces several systemic, technical, and regulatory challenges. Despite the growing recognition of CE as a sustainable framework for resource efficiency and waste minimization, the transition from conventional linear waste management models remains constrained by following factors:

1. *Technical & Infrastructure Constraints*: Segregation at source is inconsistent and mixed waste streams reduce value of recovery efforts and raise contamination risks. Treatment infrastructure is uneven and many HCFs remain outside CBWTF or captive treatment networks [10, 11]. Treatment technologies for recycling

biomedical waste are less mature and safety concerns (infection hazard, regulatory compliance) limit material recovery. Tracking, reverse logistics, and data systems (e.g., bar-coding) are still incompletely implemented across India.

2. *Regulatory, Institutional & Financial Constraints*: The BMW Rules are largely disposal-oriented (collection, transport, treatment, disposal) but do not yet fully embed circular economy concepts (reuse, recovery, recycled content mandates). Authorisation, monitoring and enforcement are variable across states; data gaps persist. For example, in some states untreated fractions remain high. Financial incentives for recovery are weak as recyclate markets for medical-waste derived materials are not well-established, and risk perception is high while the investment is limited. Coordination among multiple stakeholders (HCFs, CBWTFs, recyclers, regulators) is complex. Knowledge/awareness among small clinics and non-bedded HCFs is often low.

3. *Behavioural & Cultural Constraints*: Healthcare staff and waste-handlers may lack training/awareness of CE practices (e.g., material segregation, reuse options). The "waste" mindset dominates as biomedical waste is mentally disposed rather than treated as a resource. Patient and public perceptions about reuse/recycling of biomedical-waste-derived materials may encounter resistance due to stigma or concerns about safety.

4. *Risk & Safety Constraints*: Potential for cross-infection or contamination is high if recovery/recycling are not rigorously controlled. Strict liability for improper handling may make HCFs risk-averse to novel CE pathways. Recycling processes may carry higher cost; require high standards of sterilisation/disinfection, making business case marginal.

VI. Proposed Framework for Circularisation of BMW in India

Transitioning India's BMWM system toward a Circular Economy requires a structured and strategic approach that addresses the full lifecycle of medical materials—from procurement and design to end-of-life recovery and reuse. To operationalize this transition, a *three-layered strategic framework* is proposed, emphasizing progressive interventions across reduction, recovery, and systemic enablement. The proposed layers enabling circular economy are as follows:

Layer 1 – Reduce & Re-design

- Promote procurement policies favouring reusable/sterilisable devices and consumables (where safe).
- Encourage modular design and standardisation for ease of refurbishment.
- Perform waste-audit in HCFs to identify "avoidable" waste streams (e.g., over-packaging, unused single-use items).
- Invest in staff training for segregation and reuse protocols.

Layer 2 – Recovery & Reuse/Refurbish

- Segregation at source into reusable, recyclable, and residual hazardous streams.
- Establish certified refurbishment units for medical devices and surgical equipment (with quality & safety standards).
- Develop "take-back" programmes with manufacturers or service providers to recover end-of-life medical devices.
- Connect HCFs with recyclers accredited for handling decontaminated biomedical plastics/metals.
- Pilot energy recovery from sterilised non-infectious BMW fractions (e.g., RDF or waste-to-energy) under strict emission controls.

Layer 3 – Tracking, Incentives & Enabling Environment

- Expand digital tracking (bar-code + GPS) to all HCFs and CBWTFs to trace material flows and recovery streams.
- Introduce incentive schemes (tax rebates, subsidies) for HCFs adopting CE practices (e.g., reuse loops, material recovery).
- Publish national/state-level dashboards showing CE performance in BMWM to incentivise transparency and improvement.
- Update regulatory frameworks to incorporate circular targets (e.g., minimum reuse, material yield from BMW recycling).
- Develop standards and certification for refurbished medical devices and recycled biomedical-grade plastics.
- Promote public-private partnerships (PPP) for setting up recycling/refurbishing hubs and encourage investment in infrastructure.

6.2 Key performance indicators (KPIs) for monitoring

For monitoring progress, HCFs and regulators could adopt KPIs such as:

- % reduction in BMW generation per bed or per patient.
- % of segregated recyclable fractions recovered (plastics/metals) from BMW stream.
- % of medical devices refurbished and reused instead of new-purchase.
- % of HCFs using take-back/refurbish services.
- % of BMW material diverted for energy recovery or resource recovery rather than incineration/landfill.
- Compliance rate of HCFs (authorisation, segregation, tracking).

VII. Roadmap for Implementation of Circular Economy Pathways

Achieving a circular and sustainable BMWM system in India demands a phased, multi-dimensional roadmap that aligns policy reform, infrastructure development, operational practices, market mechanisms, and innovation. This roadmap outlines actionable pathways to integrate CE principles into the BMW sector through following five key domains.

7.1 Policy & Regulation

- Revise BMW Rules (or issue amendment/guidelines) to explicitly incorporate circular economy principles: e.g., mandatory segregation enabling recycling, incentives for reuse, recycled-content requirements for medical consumables.
- Introduce extended producer responsibility (EPR) for medical device/consumable manufacturers: take-back schemes, recycling obligations, design for reuse.
- Incentivise recovery and recycling: subsidies/Tax incentives for plants that recover materials from BMW, procurement preferences/green procurement for HCFs using recycled content.
- Strengthen monitoring & data systems: expand bar-coding/tracking, real-time dashboards of waste flows, compliance by small HCFs.

7.2 Strategic Infrastructure Investments

- Expand CBWTF capacity in underserved geographies; integrate modular-small-scale treatment for rural/remote HCFs.
- Invest in advanced treatment/processing technologies enabling safe recycling or energy recovery from BMW (autoclave + sorting + material recovery + energy generation).
- Develop centres of excellence/pilot projects for circular-BMWM to demonstrate business viability.

7.3 Operational Measures at Healthcare Facility Level

- Training & capacity building of HCF staff in segregation, waste-audit, material recovery streams.
- Waste audits: quantify volumes by stream (plastics, metals, sharps, glass) and identify recovery potential.
- Procurement policies emphasising minimal waste, reusable devices where safe, recyclable packaging, supplier take-back.

7.4 Market & Business Model Development

- Develop supply chains for recycled materials derived from BMW (e.g., purified plastics, stainless steel).
- Business models for CBWTFs: integrate traditional treatment + recovery + value-added product (e.g., sterilised recyclate) + energy generation.
- Public-private partnerships, social-enterprise models for waste segregators/recyclers focusing on BMW.
- Collaboration with recyclers/material-users, guarantee of quality and safety certifications for recyclate.

7.5 Research & Innovation

- Develop and validate safe recovery technologies for biomedical plastics, metals, glass.
- Pilot machine-vision/AI sorting systems for waste stream segregation [12].
- Life-cycle assessment (LCA) studies of CE-pathways in BMWM in Indian context (environmental, economic, social).
- Behavioural research on HCF staff, waste-handlers regarding circular practices, and design of interventions.

VIII. Conclusion

India's biomedical waste challenge is at crossroads: escalating volumes, infrastructural bottlenecks, and growing environmental/health concerns underscore the limitations of the existing linear disposal model. Embracing a circular economy paradigm offers a pathway to reduce waste generation, recover material and energy value, improve safety and sustainability, reduce costs in the long run, relieve pressure on waste infrastructure, and create new resource-loops in healthcare. The shift toward a circular economy in BMWM in India is both necessary and feasible. While opportunities are abound (material recovery, reusable devices, energy recovery, take-back schemes), realising circularity in BMWM will require revised policy frameworks embedding CE, investment in infrastructure/technology, operational changes in HCFs, market development for recovered materials, strong monitoring/metrics, stakeholder engagement and capacity building. With concerted effort, India can move from linear treat-and-dispose models to circular and sustainable systems for biomedical waste, contributing to public health, environmental protection and sustainable development. A phased implementation may be prudent: starting with low-hanging fruit (e.g., improved segregation, material recovery of non-hazardous plastics/metals), and then scaling to more advanced recovery/energy systems. Pilot projects and demonstration models are critical to build confidence and economics.

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