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Scope of Using Alternative Technology for Bio Medical Waste Management: An Indian Approach

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Abstract:
Biomedical waste management presents significant challenges to healthcare systems worldwide, with particularly complex implications in developing countries like India. This comprehensive review examines the current status and future scope of alternative technologies for biomedical waste (BMW) management in the Indian context. The generation of biomedical waste in hospitals poses substantial hazards to healthcare workers and the environment, necessitating effective management strategies. Traditional methods such as incineration, while widely used, present environmental concerns related to toxic emissions. This paper explores emerging alternative technologies including plasma pyrolysis, microwave-assisted disinfection, electron beam treatment, and bioremediation approaches that offer promising solutions for safer and more sustainable BMW management. The research highlights how these technologies address the limitations of conventional methods while considering India's specific socioeconomic context. Economic viability analysis reveals opportunities for cost-effective implementation across various healthcare facility scales. The paper also critically examines India's regulatory framework through the Biomedical Waste Management Rules of 2016 and subsequent amendments, identifying significant implementation challenges and successes.

Keywords: Biomedical waste management, alternative technologies, plasma pyrolysis, microwave treatment, bioremediation, healthcare facilities, environmental impact, cost-effectiveness, regulatory compliance

Introduction

Biomedical waste (BMW) encompasses waste generated during the diagnosis, treatment, or immunization of humans or animals, research activities, and the production or testing of biological materials. According to India's Biomedical Waste Management Rules of 2016, it includes items contaminated with blood, body fluids, human anatomical waste, animal waste, microbiological waste, and biotechnology waste (Ministry of Environment, Forest and Climate Change, 2016). The management of such waste presents significant challenges due to its infectious, toxic, and hazardous nature, posing risks to healthcare workers, waste handlers, patients, communities, and the environment.

India's expanding healthcare sector generates substantial quantities of biomedical waste estimated at 484 tonnes per day (TPD) from over 168,869 healthcare facilities (HCFs), with only 447 TPD receiving proper treatment (Jain et al., 2017). This leaves approximately 37 TPD untreated, creating significant environmental and public health concerns[3]. The

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[3] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

indiscriminate management of biomedical waste in India has attracted attention from the highest judicial bodies due to its serious implications for public health and environmental safety[4].

Traditional biomedical waste management in India has primarily relied on incineration, autoclaving, and deep burial methods. However, these conventional approaches present considerable limitations, including the generation of toxic emissions from incinerators, high operational costs, and environmental contamination. Additionally, inadequate infrastructure, insufficient training of healthcare personnel, and low awareness levels have further complicated effective biomedical waste management across the country[5].

The rise in needle stick injuries among waste handlers, primarily resulting from improper segregation practices, underscores the urgent need for improved BMW management protocols[2]. Furthermore, incidents like the 2009 hepatitis B outbreak in Gujarat, where approximately 240 people contracted the disease following the reuse of unsterilized syringes, highlight the severe public health consequences of improper medical waste disposal practices[6].

Recent years have witnessed growing interest in alternative technologies for biomedical waste management that offer more environmentally sustainable and economically viable solutions. These include plasma pyrolysis, microwave-based disinfection systems, electron beam technology, bioremediation approaches, and other innovative methods that promise to address the limitations of conventional techniques while ensuring safe disposal of hazardous medical waste[7].

This paper aims to comprehensively evaluate the scope of using alternative technologies for biomedical waste management in India, examining their technical feasibility, economic viability, environmental impacts, and regulatory compatibility. By exploring both existing practices and emerging innovations, this research seeks to identify sustainable approaches that align with India's specific socioeconomic context, infrastructure capabilities, and healthcare needs. The study also analyzes the current regulatory framework governing biomedical waste management in India and assesses its effectiveness in promoting the adoption of alternative technologies for safer and more efficient waste disposal practices.

Existing Technology

The management of biomedical waste in India has traditionally relied on several established technologies and methodologies. Understanding these existing approaches provides crucial context for evaluating the potential of alternative technologies and identifying areas for improvement in the current waste management paradigm.

Incineration

Incineration has long been the predominant method for treating biomedical waste in India. This thermal process involves the combustion of waste at high temperatures, typically between 800-1200°C, to convert it into ash, flue gas, and heat. While effective at reducing waste volume and destroying pathogens, conventional incinerators have drawn criticism for their significant environmental footprint, particularly concerning air pollution[8].

The Biomedical Waste Management Rules of 2016 specify that incinerators must maintain specific standards, including a two-seconds retention time in the secondary combustion chamber and adequate air pollution control devices to comply with emission norms[9]. However, studies indicate that many incinerators in Indian healthcare facilities fail to meet these

[4] Mukunda C. Sahoo, Jawahar S. K. Pillai and Biswajeevan Sahoo, "Exploring Biomedical Waste Management Practices Among Healthcare Professionals: A Study From a Tertiary Care Teaching Hospital in Eastern India," 16 *Cureus* e61823 (2024).

[5] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.

[6] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

[7] "CPCB | Central Pollution Control Board,"*available at*: https://cpcb.nic.in/states-of-new-technologies-for-treatment-disposal-of-bmw/ (last visited August 10, 2024).

[8] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

[9] Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016

standards, resulting in the release of harmful pollutants such as dioxins, furans, and heavy metals into the atmosphere[10]. These toxic emissions pose serious threats to human health and environmental integrity, leading to a gradual shift toward alternative technologies.

Autoclaving

Autoclaving represents another widely used method for treating biomedical waste in India. This steam-based sterilization process utilizes high-pressure saturated steam at 121°C or higher to decontaminate infectious waste. The technique is particularly effective for microbial cultures, sharps, and other contaminated items but requires proper segregation of waste at the source to ensure effectiveness[11].

While autoclaving offers a relatively environmentally friendly alternative to incineration for certain waste categories, it has several limitations. The process does not reduce waste volume significantly, requires substantial energy inputs, and is unsuitable for treating anatomical waste, chemotherapy drugs, and volatile organic compounds. Additionally, the efficacy of autoclaving depends heavily on proper waste segregation practices, which remain inconsistent across many Indian healthcare facilities[12].

Chemical Disinfection

Chemical disinfection involves treating biomedical waste with chemical agents such as sodium hypochlorite, chlorine dioxide, or peracetic acid to neutralize pathogens. This method is commonly employed for liquid waste, microbiological waste, and sharps in many Indian healthcare settings, particularly where other treatment options are limited.

However, chemical disinfection presents several challenges, including incomplete destruction of pathogens, environmental concerns related to chemical discharges, and occupational health risks to waste handlers. The effectiveness of this method also varies significantly depending on the concentration of the disinfectant, contact time, and waste characteristics, making standardization difficult across diverse healthcare settings[13].

Deep Burial

In rural or remote areas where access to centralized treatment facilities is limited, deep burial pits have served as a common disposal method for biomedical waste. The BMWM Rules of 2016 permit this practice only in specific circumstances, such as for healthcare facilities located in isolated areas and for certain waste categories like anatomical waste[1].

Deep burial involves digging pits lined with impermeable materials and burying the waste under layers of lime and soil. However, this method poses significant risks of groundwater contamination, soil pollution, and accidental exposure if not properly constructed and maintained. Consequently, regulatory authorities have increasingly restricted its use to exceptional circumstances only[14].

Current Practices in Indian Healthcare Facilities

Despite regulatory frameworks mandating proper waste management, studies reveal substantial gaps in practice across Indian healthcare facilities. A comprehensive evaluation of biomedical waste management practices in a tertiary care hospital in Eastern India found that compliance with waste segregation protocols was initially as low as 57%, highlighting

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[10] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

[11] Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016

[12] Mukunda C. Sahoo, Jawahar S. K. Pillai and Biswajeevan Sahoo, "Exploring Biomedical Waste Management Practices Among Healthcare Professionals: A Study From a Tertiary Care Teaching Hospital in Eastern India," 16 *Cureus* e61823 (2024).

[13] Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016

[14] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

significant challenges in implementation[15].

A study conducted across Primary Health Centers in Sikkim revealed that while 66% of healthcare workers possessed adequate knowledge about proper BMW management, only 60% demonstrated good practice scores, indicating a notable gap between awareness and actual practice[16]. Similar findings have been reported across multiple studies, suggesting systematic challenges in translating knowledge into consistent practices across different healthcare settings[17].

Common issues identified include:

1. Improper segregation of waste at the source, leading to mixed waste streams that complicate treatment and increase hazards[18].
2. Insufficient pre-treatment of laboratory and highly infectious waste before disposal.
3. Inadequate use of color-coded bags and containers as stipulated by regulations[19].
4. Limited training opportunities for healthcare workers, particularly supportive medical staff and waste handlers.
5. Deficient infrastructure for temporary storage and transport of segregated waste[20].

While India has established 198 Common Bio-Medical Waste Treatment Facilities (CBMWTFs) with an additional 28 under construction, significant gaps remain in coverage, with many healthcare facilities still lacking access to proper treatment and disposal options within the recommended 75-kilometer radius[21]. Consequently, a considerable portion of biomedical waste remains either untreated or subjected to inappropriate disposal methods, posing ongoing risks to public health and the environment.

Experimental Technology

As limitations of conventional biomedical waste management approaches become increasingly apparent, several innovative technologies have emerged as potential alternatives. These experimental technologies aim to address the environmental, economic, and operational challenges associated with traditional methods while ensuring effective pathogen destruction and waste volume reduction. This section explores key innovative approaches being developed and tested for biomedical waste management in India.

Plasma Pyrolysis Technology

Plasma pyrolysis represents one of the most promising alternative technologies for biomedical waste management and has received provisional approval from India's Central Pollution Control Board (CPCB)[22]. This innovative technology uses plasma torches to generate extremely high temperatures (plasma core temperature >5000°C) that convert electrical energy into thermal energy in an efficient manner[23]. Unlike conventional incineration, plasma pyrolysis occurs in an oxygen-starved environment, resulting in thermal disintegration rather than combustion.

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[15] Mukunda C. Sahoo, Jawahar S. K. Pillai and Biswajeevan Sahoo, "Exploring Biomedical Waste Management Practices Among Healthcare Professionals: A Study From a Tertiary Care Teaching Hospital in Eastern India," 16 *Cureus* e61823 (2024).

[16] Sunita Thapa and Nasrin B. Laskar, "Biomedical waste management among healthcare workers in a Primary Health Centre in Sikkim, India—A KAP study," 13 *Journal of Education and Health Promotion* 378 (2024).

[17] Yuvappreya Krishnamurthy et al., "Predictors of biomedical waste management practices among staff nurses of a tertiary care teaching hospital in India," 13 *Journal of Education and Health Promotion* 78 (2024).

[18] Sunita Thapa and Nasrin B. Laskar, "Biomedical waste management among healthcare workers in a Primary Health Centre in Sikkim, India—A KAP study," 13 *Journal of Education and Health Promotion* 378 (2024).

[19] *Ibid.*

[20] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.

[21] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

[22] "CPCB | Central Pollution Control Board,"*available at*: https://cpcb.nic.in/states-of-new-technologies-for-treatment-disposal-of-bmw/ (last visited August 10, 2024).

[23] "Plasma Pyrolysis Technology for Safe Disposal of Biomedical Waste,"*available at*: http://www.plasmaindia.com/Pyrolysis.html (last visited August 10, 2024).

The process fragments organic mass into hydrogen, carbon monoxide, and lower hydrocarbons, with nearly 99% of organic material converting into combustible gases that can be utilized as fuel for heating applications or power generation[24]. A significant advantage of plasma pyrolysis is its ability to eliminate toxic molecules such as dioxins, furans, and polyaromatic hydrocarbons that are typically associated with conventional incineration processes[25].

Researchers at the Facilitation Centre for Industrial Plasma Technologies in India have further innovated this technology through the development of a graphite torch system that exploits gas generation in the pyrolysis of organic matter. This endogenous gas feed concept, patented in 2007, offers a 35% gain in energy efficiency and reduces electrode erosion rates, enhancing the overall sustainability of the process[26].

The BMWM Rules of 2016 explicitly recognize plasma pyrolysis as an approved method for treating certain categories of biomedical waste, particularly anatomical waste, where incineration would otherwise be required[5]. This regulatory endorsement has facilitated the gradual adoption of plasma pyrolysis systems across various healthcare settings in India, although implementation remains limited by factors including high initial capital costs and technical expertise requirements[27].

Microwave-Based Disinfection Systems

Microwave technology has emerged as another promising alternative for biomedical waste treatment in India. This process utilizes microwave radiation to treat medical waste, functioning similarly to a more powerful version of household microwave ovens but operating at 2450 Hz[28]. Systems can be installed either as on-site facilities within healthcare institutions or deployed as mobile treatment units, offering flexibility in application.

The OptiMaser system, developed and patented in India, represents an innovative application of Microwave-assisted Cold Sterilization (MACS) Technology operating at 70°C[29]. This technology has been implemented across all All India Institutes of Medical Sciences (AIIMS) facilities and offers several advantages over traditional methods, including:

1. PLC-based automated waste management processes requiring minimal operator intervention
2. Reduced risk of healthcare-associated infections by curtailing infection spread
3. Almost negligible running and maintenance costs
4. Zero emissions and discharges, enhancing environmental sustainability
5. Processing times of 7-30 minutes based on waste load type

The microwave treatment process typically includes front-end shredding of waste to increase treatment efficacy and reduce final waste volume. Water is added if the waste is dry, as microwave disinfection works by directly affecting water molecules rather than solid components. When sufficient power is applied, water converts to steam, heating all surrounding waste to approximately 100°C[30].

Unlike autoclaving, which provides heat from outside the waste (similar to conventional ovens), microwave units transmit energy as microwaves that generate heat inside the wet waste, resulting in more efficient and thorough disinfection[31]. This process is particularly effective for treating infectious wastes but is not recommended by the

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24 *Ibid.*
25 *Ibid.*
26 The Indian Practitioner, "Plasma Pyrolysis of Bio-medical Waste" *The Indian Practitioner*, 2022*available at*: https://theindianpractitioner.com/plasma-pyrolysis-of-bio-medical-waste/ (last visited May 18, 2025).
27 Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).
28 "Treating Medical Waste with Microwaves, and Irradiation,"*available at*: https://www.malsparo.com/treat2.htm (last visited August 10, 2024).
29 "Microwave based medical waste disinfection system, OptiMaser by Avantor,"*available at*: https://www.avantorsciences.com/in/en/product/28819197/null (last visited August 10, 2024).
30 "Treating Medical Waste with Microwaves, and Irradiation,"*available at*: https://www.malsparo.com/treat2.htm (last visited August 10, 2024).
31 *Ibid.*

Environmental Protection Agency (EPA) for pathological waste treatment[32].

Electron Beam Technology

Electron beam technology represents an emerging approach for treating hospital wastewater and certain types of solid biomedical waste. This technique uses accelerated electrons to treat waste, effectively removing chemical oxygen demand (COD), pathogenic bacteria, and viruses. A demonstration project implemented in Hubei, China during the COVID-19 pandemic showed promising results for hospital sewage treatment, providing valuable insights for potential application in the Indian context[33].

The technology demonstrated that with an absorbed dose of 4 kGy, effluent COD concentration was consistently maintained below 30 mg/L, and fecal Escherichia coli levels remained below 50 MPN/L[34]. For virus inactivation, higher absorbed doses between 30-50 kGy were required, achieving complete removal of certain viruses including Hepatitis A virus (HAV) and Astrovirus (ASV)[35].

While electron beam technology has not yet been widely adopted in India for biomedical waste treatment, its demonstrated effectiveness in pathogen elimination without generating secondary pollutants makes it a potential candidate for future implementation, particularly for liquid biomedical waste streams that currently present significant treatment challenges.

Bioremediation Approaches

Bioremediation offers an environmentally sustainable approach to biomedical waste management by employing microorganisms, plants, and their enzymatic processes to degrade or transform hazardous components into less toxic forms. This method is particularly promising for treating biomedical waste with high organic content and has gained increasing attention as a complement to physical and chemical treatment methods[36].

Various techniques encompassed under bioremediation include:

1. **Microbial Remediation**: Utilizes bacteria, fungi, and algae to break down organic pollutants in biomedical waste. These microorganisms possess inherent physiological, biochemical, and genetic properties that facilitate the degradation of complex organic compounds, including those found in hospital waste[37].
2. **Phytoremediation**: Employs plants and their associated rhizospheric microorganisms to degrade, eliminate, alter, or contain toxic materials present in soils, sediments, and wastewater from healthcare facilities. This approach has shown potential for handling various types of pollutants, including radioactive waste from hospitals[38].
3. **Enzymatic Treatment**: Involves using specific enzymes to catalyze the breakdown of biomedical waste components, offering a targeted approach to waste degradation.

Bioremediation is generally more economical and sustainable than conventional physical and chemical treatments, making it particularly relevant for resource-constrained settings in India[39]. However, the technology remains in experimental stages for biomedical waste applications, with ongoing research focused on optimizing microbial strains, enhancing degradation rates, and developing standardized protocols for different waste streams.

Sharp Blaster Technology

The Sharp Blaster technology represents an innovative approach specifically designed for the safe disposal of needles

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32 *Ibid.*
33 "Treatment of hospital wastewater by electron beam technology: Removal of COD, pathogenic bacteria and viruses - PubMed,"*available at*: https://pubmed.ncbi.nlm.nih.gov/36055595/ (last visited May 18, 2025).
34 *Ibid.*
35 *Ibid.*
36 Mohd Sajjad Ahmad Khan, "Applications of Bioremediation in Biomedical Waste Management: Current and Future Prospects," 67 *Brazilian Archives of Biology and Technology* e24230161 (2024).
37 *Ibid.*
38 *Ibid.*
39 *Ibid.*

and sharps, which constitute a significant hazard in biomedical waste streams. This technology has received provisional approval from India's Central Pollution Control Board and offers a targeted solution to the persistent problem of needle stick injuries among healthcare workers and waste handlers.

The system works by disintegrating sharps waste, effectively rendering it non-reusable while also disinfecting it. While not intended as a comprehensive solution for all biomedical waste categories, Sharp Blaster technology addresses a critical component of the waste stream that poses disproportionate risk.

Need for New Technology

The pressing requirement for alternative technologies in biomedical waste management stems from various limitations associated with conventional methods and evolving challenges in the healthcare landscape. This section examines the factors driving the need for innovative approaches to biomedical waste management in India.

Limitations of Conventional Methods

Traditional biomedical waste management technologies, while established, present significant drawbacks that necessitate exploration of alternatives. Incineration, the most widely used method, generates toxic air pollutants including dioxins, furans, and heavy metals that pose serious environmental and public health risks[40]. The ash produced during incineration often contains hazardous compounds requiring specialized disposal, creating additional environmental challenges[41]. These environmental concerns have led to increasing regulatory restrictions on incineration processes worldwide, including in India.

Autoclaving, while environmentally preferable to incineration for certain waste streams, demonstrates limited effectiveness for anatomical waste, chemotherapeutic drugs, and chemical waste. The process requires significant energy inputs and does not substantially reduce waste volume, leading to continued disposal challenges[42]. Additionally, autoclaving efficacy depends heavily on proper waste segregation, which remains inconsistent across many Indian healthcare facilities[43].

Deep burial pits, still utilized in some rural and remote areas, pose substantial risks of groundwater contamination and soil pollution. Their use is increasingly restricted by regulations due to these environmental concerns, yet alternatives remain limited in resource-constrained settings[1][5].

Environmental Imperatives

Environmental considerations have become increasingly central to biomedical waste management policy and practice. India's National Green Tribunal and Supreme Court have issued multiple directives aimed at minimizing the environmental impact of healthcare waste, reflecting growing recognition of the ecological implications of inappropriate waste disposal methods[44].

The Biomedical Waste Management Rules of 2016, which replaced the earlier 1998 rules, explicitly aim to "improve the collection, segregation, processing, treatment and disposal of these biomedical wastes in an environmentally sound management thereby, reducing the bio-medical waste generation and its impact on the environment". This regulatory evolution reflects heightened awareness of environmental considerations and sets more stringent standards for waste treatment technologies.

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[40] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).
[41] *Ibid.*
[42] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.
[43] Sunita Thapa and Nasrin B. Laskar, "Biomedical waste management among healthcare workers in a Primary Health Centre in Sikkim, India—A KAP study," 13 *Journal of Education and Health Promotion* 378 (2024).
[44] Mukunda C. Sahoo, Jawahar S. K. Pillai and Biswajeevan Sahoo, "Exploring Biomedical Waste Management Practices Among Healthcare Professionals: A Study From a Tertiary Care Teaching Hospital in Eastern India," 16 *Cureus* e61823 (2024).

The rules further mandate the phasing out of chlorinated plastic bags, gloves, and blood bags (excluding blood bags) by March 27, 2019, indicating a shift toward more environmentally sustainable practices in the healthcare sector[45]. Such regulatory changes necessitate the adoption of technologies compatible with non-chlorinated materials and capable of treating diverse waste streams with minimal environmental impact.

Healthcare Sector Growth

India's healthcare sector is experiencing rapid expansion, with increasing numbers of healthcare facilities and growing service utilization across both urban and rural areas. Current estimates indicate that India has over 168,869 healthcare facilities generating biomedical waste[46], and this number continues to rise with healthcare infrastructure development.

The COVID-19 pandemic further accelerated biomedical waste generation, creating unprecedented challenges for existing waste management systems and highlighting vulnerabilities in the current infrastructure[47]. As healthcare services continue to expand to meet the needs of India's growing population, the volume of biomedical waste is projected to increase substantially, necessitating more efficient and scalable treatment technologies.

Occupational Safety Concerns

The rise in needle stick injuries among healthcare workers and waste handlers represents a severe occupational hazard directly linked to improper segregation and disposal of biomedical waste[48]. These injuries pose significant risks of bloodborne pathogen transmission, including hepatitis B, hepatitis C, and HIV, underscoring the urgent need for safer waste handling technologies and protocols.

Studies from tertiary care hospitals in India reveal concerning gaps in knowledge and practice regarding biomedical waste management among healthcare professionals, indicating systemic issues that technology alone cannot address but that improved technologies might help mitigate[49]. Alternative technologies that minimize manual handling and processing of hazardous waste components could significantly reduce occupational exposure risks.

Infrastructure Limitations

India currently operates 198 Common Bio-Medical Waste Treatment Facilities (CBMWTFs) with an additional 28 under construction[50]. However, these facilities remain insufficient to serve all healthcare institutions within the recommended 75-kilometer radius specified by regulations. Consequently, many healthcare facilities either manage waste on-site with suboptimal methods or transport it over excessive distances, increasing environmental footprints and operational costs.

The BMWM Rules stipulate that healthcare facilities should not establish on-site treatment facilities if a CBMWTF is available within 75 kilometers. This provision aims to promote centralized, efficient waste treatment but becomes problematic when such facilities are unavailable. Alternative technologies that can be safely and effectively operated on a smaller scale within healthcare facilities could help address this infrastructure gap, particularly in underserved regions.

Scientific and Technological Advancements

Recent scientific and technological innovations have created opportunities to overcome limitations of traditional waste management approaches. Advancements in materials science, microbiology, electronic controls, and engineering have

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[45] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.

[46] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

[47] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.

[48] Mukunda C. Sahoo, Jawahar S. K. Pillai and Biswajeevan Sahoo, "Exploring Biomedical Waste Management Practices Among Healthcare Professionals: A Study From a Tertiary Care Teaching Hospital in Eastern India," 16 *Cureus* e61823 (2024).

[49] Yuvappreya Krishnamurthy et al., "Predictors of biomedical waste management practices among staff nurses of a tertiary care teaching hospital in India," 13 *Journal of Education and Health Promotion* 78 (2024).

[50] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

enabled the development of more efficient, environmentally sustainable, and economically viable treatment technologies[14][12][4].

The provisional approval granted by the Central Pollution Control Board to innovative technologies like plasma pyrolysis, Sharp Blaster, and microwave treatment systems reflects official recognition of these scientific advancements and their potential to transform biomedical waste management practices in India[9][1]. These technologies represent not only incremental improvements over existing methods but potentially paradigm-shifting approaches to addressing the multifaceted challenges of biomedical waste.

Economic Factors

The economic dimensions of biomedical waste management significantly influence technology adoption decisions across India's diverse healthcare landscape. Understanding these factors is essential for evaluating the feasibility and sustainability of alternative technologies.

Implementation Costs

The initial capital expenditure required for establishing alternative biomedical waste treatment technologies represents a significant barrier, particularly for smaller healthcare facilities and those in resource-constrained settings. Advanced technologies like plasma pyrolysis require substantial upfront investment in specialized equipment, infrastructure modifications, and technical expertise[51]. For instance, while plasma pyrolysis offers environmental advantages over conventional incineration, its higher implementation cost has limited widespread adoption beyond larger institutions and centralized facilities.

Microwave-based systems, while generally less expensive than plasma technologies, still require significant initial investment. The OptiMaser system implemented across AIIMS facilities demonstrates that while operational costs may be lower in the long run, the initial procurement and installation expenses can be substantia. These capital costs must be evaluated against the healthcare facility's size, waste generation volume, and financial capacity.

For Common Bio-Medical Waste Treatment Facilities (CBMWTFs), which serve multiple healthcare institutions, the economic calculations become more complex. These centralized facilities must balance substantial capital investments against service fees collected from client healthcare facilities, which may have limited ability to pay, particularly in smaller towns and rural areas[52]. This economic model influences both technology selection and geographical distribution of treatment facilities.

Operational Costs

Ongoing operational expenses vary significantly across different biomedical waste treatment technologies. Conventional incineration incurs substantial costs for fuel, emissions control, ash disposal, and regulatory compliance monitoring[53]. In contrast, alternative technologies often promise reduced operational expenses as a key advantage.

Microwave systems like OptiMaser advertise "almost negligible running and maintenance cost" with "zero consumables required"[1]. This operational efficiency derives from lower energy consumption, reduced need for consumable materials, and minimal maintenance requirements compared to conventional technologies. Similarly, bioremediation approaches offer potential operational savings through natural degradation processes that require minimal external inputs once established[14].

For healthcare facilities considering on-site treatment versus outsourcing to CBMWTFs, the economic equation involves comparing the combined capital and operational costs of in-house systems against service fees charged by external providers. The BMWM Rules' stipulation that facilities must use CBMWTFs if available within 75 kilometers introduces

[51] "Plasma Pyrolysis Technology for Safe Disposal of Biomedical Waste," *available at*: http://www.plasmaindia.com/Pyrolysis.html (last visited August 10, 2024).

[52] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

[53] *Ibid.*

a regulatory dimension to this economic decision[5].

Labor and Training Requirements

The human resource dimension of biomedical waste management represents a significant economic factor that varies across technologies. Conventional waste management approaches often require extensive manual handling, sorting, and processing, necessitating larger workforces and presenting occupational safety concerns that may result in healthcare costs and lost productivity[54].

Alternative technologies frequently offer advantages through automation and simplified processes. For example, the OptiMaser system features "PLC based automated waste management process" requiring "zero skilled labor"[55]. This reduction in labor intensity can yield substantial economic benefits, particularly in settings with personnel constraints or high labor costs.

However, all biomedical waste management technologies require some level of training for effective implementation. Studies across Indian healthcare facilities consistently identify training gaps as significant barriers to effective waste management[56]. The economic implications include both direct costs of training programs and indirect costs associated with improper waste management resulting from inadequate training.

Economic Benefits and Return on Investment

When evaluating the economic viability of alternative technologies, potential benefits must be considered alongside costs. These benefits include:

1. **Reduced healthcare-associated infection costs**: Improved waste management can decrease infection transmission within healthcare facilities, potentially reducing treatment costs, length of stay, and associated financial implications.
2. **Avoided environmental remediation expenses**: Preventing environmental contamination through improved waste treatment eliminates potential future costs of environmental cleanup and public health interventions.
3. **Resource recovery potential**: Some alternative technologies enable recovery of valuable materials or energy from waste streams. For instance, plasma pyrolysis generates combustible gases that can be utilized for heating or power generation, offsetting energy costs[57].
4. **Regulatory compliance savings**: As environmental regulations become increasingly stringent, technologies that ensure compliance can prevent costly penalties, operational disruptions, and reputation damage.
5. **Volume reduction benefits**: Technologies that significantly reduce waste volume decrease subsequent transportation and disposal costs, which can be substantial for healthcare facilities generating large quantities of waste.

Scale Considerations

The economic viability of different biomedical waste treatment technologies varies substantially based on the scale of operation. Large hospitals and centralized treatment facilities benefit from economies of scale that make capital-intensive technologies more feasible. In contrast, smaller healthcare facilities frequently face economic barriers to adopting advanced technologies due to insufficient waste volumes to justify the investment[15].

A waste-to-energy feasibility study using Complex Proportional Assessment (COPRAS) methodology identified annual energy production and initial investment as the most significant technical and economic factors influencing technology

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[54] Sunita Thapa and Nasrin B. Laskar, "Biomedical waste management among healthcare workers in a Primary Health Centre in Sikkim, India—A KAP study," 13 *Journal of Education and Health Promotion* 378 (2024).
[55] "Microwave based medical waste disinfection system, OptiMaser by Avantor," *available at*: https://www.avantorsciences.com/in/en/product/28819197/null (last visited August 10, 2024).
[56] Sunita Thapa and Nasrin B. Laskar, "Biomedical waste management among healthcare workers in a Primary Health Centre in Sikkim, India—A KAP study," 13 *Journal of Education and Health Promotion* 378 (2024).
[57] "Plasma Pyrolysis Technology for Safe Disposal of Biomedical Waste," *available at*: http://www.plasmaindia.com/Pyrolysis.html (last visited August 10, 2024).

selection[58]. This analysis suggests that optimal technology selection depends heavily on facility scale and waste generation volumes, with different solutions proving most economical at different operational scales.

For rural healthcare facilities with limited resources and waste volumes, simpler and less capital-intensive technologies may prove more economically viable despite potential environmental trade-offs[59]. This economic reality underscores the importance of developing scalable solutions that can be appropriately sized and configured for diverse healthcare settings across India.

Environmental Factors

The environmental implications of biomedical waste management technologies are increasingly central to policy decisions and technology selection in India. This section examines the environmental considerations driving the shift toward alternative technologies and their comparative environmental impacts.

Pollution Concerns with Traditional Methods

Conventional biomedical waste treatment methods, particularly incineration, have raised significant environmental concerns that have motivated the search for alternatives. Incineration processes, especially those in poorly maintained or outdated facilities, emit hazardous air pollutants including particulate matter, heavy metals, acid gases, and persistent organic pollutants such as dioxins and furans[60]. These emissions contribute to air quality degradation and pose public health risks to surrounding communities.

The improper disposal of incinerator ash, which often contains concentrated levels of heavy metals and other hazardous compounds, presents additional environmental risks through potential soil contamination and groundwater pollution[61]. These environmental concerns have prompted increasingly stringent emission standards and regulatory restrictions on incineration practices in India and globally.

Chemical disinfection methods, while less environmentally harmful than uncontrolled incineration, introduce their own environmental challenges through the discharge of chemical residues into wastewater systems. These disinfectants may interfere with biological wastewater treatment processes and potentially contribute to antimicrobial resistance development in environmental bacteria[62].

Deep burial practices, though still permitted in limited circumstances under the BMWM Rules, pose risks of soil and groundwater contamination, particularly in areas with high water tables or inadequate geological barriers[63]. The environmental persistence of certain biomedical waste components, including pharmaceuticals, pathogens, and plastics, exacerbates these concerns.

Environmental Benefits of Alternative Technologies

Alternative biomedical waste treatment technologies offer significant environmental advantages that have driven their development and gradual adoption. These benefits vary across technologies but generally include reduced emissions, lowered resource consumption, and minimized environmental persistence of waste components.

Plasma pyrolysis technology operates in an oxygen-starved environment, minimizing the formation of toxic compounds associated with combustion processes. The high-temperature plasma effectively destroys organic materials without

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[58] "Waste-to-energy technologies' technological and economic viability for investment in India: A COPRAS Method," 1 *Recent trends in Management and Commerce* 153–60 (2020).
[59] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.
[60] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).
[61] *Ibid.*
[62] Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016
[63] *Ibid.*

generating dioxins, furans, or polyaromatic hydrocarbons typically associated with conventional incineration[64]. Additionally, the process converts approximately 99% of organic matter into combustible gases that can be utilized as an energy source, contributing to resource recovery and reduced fossil fuel consumption[65].

Microwave treatment systems demonstrate environmental advantages through their minimal emissions and discharges. The OptiMaser system, for example, advertises "zero emissions and discharges" and identifies itself as "waste reducing, water efficient, energy efficient"[66]. By avoiding combustion processes entirely, microwave disinfection eliminates concerns related to air pollutant emissions while effectively inactivating pathogens.

Electron beam technology, primarily applied to hospital wastewater treatment, offers environmental benefits through chemical-free pathogen inactivation and organic contaminant degradation. Research demonstrates that this technology effectively removes chemical oxygen demand (COD) and pathogens without introducing additional chemical contaminants into the environment[67]. This approach shows particular promise for addressing pharmaceutical and antimicrobial contamination in hospital effluents, which represent emerging environmental concerns.

Bioremediation approaches represent perhaps the most environmentally harmonious treatment option, utilizing natural biological processes to degrade or transform hazardous components of biomedical waste. These methods avoid the energy-intensive processes, chemical inputs, and emissions associated with conventional treatment technologies, instead harnessing microbial metabolism and plant uptake mechanisms[68]. Particularly for biomedical waste components with high organic content, bioremediation offers a sustainable treatment pathway with minimal environmental footprint.

Climate Change Considerations

The climate impact of biomedical waste management technologies has gained increasing attention as India works to meet its national climate commitments. Energy-intensive treatment methods contribute to greenhouse gas emissions both directly through combustion processes and indirectly through electricity consumption. Alternative technologies with improved energy efficiency present opportunities for reducing these climate impacts.

Waste-to-energy approaches, including advanced plasma pyrolysis systems that capture and utilize combustible gases, offer potential climate benefits by offsetting fossil fuel consumption[69]. However, comprehensive lifecycle assessments are needed to accurately quantify net climate impacts, accounting for factors including embedded carbon in equipment manufacturing, operational energy requirements, and avoided emissions from displaced energy sources.

The climate implications of transportation requirements for different waste management approaches also merit consideration. Centralized treatment facilities may offer operational efficiencies but require transportation of waste over significant distances, while decentralized on-site technologies eliminate transportation emissions but may operate at lower efficiencies[70]. Finding the optimal balance between centralization and distribution remains a challenge with significant climate implications.

Microplastic Concerns

The problem of microplastic pollution has emerged as an environmental concern relevant to biomedical waste

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64 “Plasma Pyrolysis Technology for Safe Disposal of Biomedical Waste,” *available at*: http://www.plasmaindia.com/Pyrolysis.html (last visited August 10,2024).

65 *Ibid.*

66 “Microwave based medical waste disinfection system, OptiMaser by Avantor,” *available at*: https://www.avantorsciences.com/in/en/product/28819197/null (last visited August 10, 2024).

67 “Treatment of hospital wastewater by electron beam technology: Removal of COD, pathogenic bacteria and viruses - PubMed,” *available at*: https://pubmed.ncbi.nlm.nih.gov/36055595/ (last visited August 10, 2024).

68 Mohd Sajjad Ahmad Khan, “Applications of Bioremediation in Biomedical Waste Management: Current and Future Prospects,” 67 *Brazilian Archives of Biology and Technology* e24230161 (2024).

69 “Waste-to-energy technologies’ technological and economic viability for investment in India: A COPRAS Method,” 1 *Recent trends in Management and Commerce* 153–60 (2020).

70 Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016

management, particularly given the healthcare sector's substantial plastic consumption. Conventional treatment methods may fragment but not fully destroy plastic components, potentially contributing to environmental microplastic accumulation[71].

High-temperature technologies like plasma pyrolysis offer advantages for addressing this concern through complete molecular breakdown of plastic materials[72]. The Biomedical Waste Management Rules' mandate to phase out chlorinated plastics further addresses this issue by promoting transition to more environmentally benign alternatives[73].

Research on recycling and reusing methods for plastic waste, including those generated in healthcare settings, indicates emerging opportunities for more sustainable approaches to managing this waste stream in India[16]. However, application to biomedical plastics presents unique challenges due to contamination concerns and infection control requirements, necessitating specialized approaches.

Cost-Effective Technology

Identifying economically viable technologies for biomedical waste management represents a critical challenge, particularly in India's diverse healthcare landscape encompassing sophisticated urban hospitals and resource-constrained rural facilities. This section examines technologies that balance environmental performance with economic feasibility across different operational contexts.

Microwave Disinfection Systems

Microwave-based technologies have emerged as particularly cost-effective solutions for biomedical waste management in the Indian context. While requiring moderate initial investment, these systems offer several economic advantages that enhance their overall cost-effectiveness, especially for medium-sized healthcare facilities.

The OptiMaser system, developed and implemented widely across Indian healthcare institutions including all AIIMS facilities, exemplifies the cost-effectiveness potential of microwave technology. Key economic advantages include:

1. **Low operational costs**: The system requires minimal consumables and features "almost negligible running and maintenance cost," substantially reducing the total cost of ownership compared to technologies requiring ongoing fuel, chemical inputs, or frequent part replacements[74].
2. **Energy efficiency**: Microwave disinfection typically consumes less energy than thermal alternatives like autoclaving or incineration, reducing utility expenses over the operational lifetime[75].
3. **Rapid processing cycles**: With treatment times ranging from 7-30 minutes depending on waste load type, microwave systems offer high throughput capacity with minimal operator intervention, optimizing labor utilization[76].
4. **Reduced secondary waste management costs**: Unlike incineration, microwave treatment does not generate ash requiring specialized disposal, eliminating associated handling and disposal expenses.
5. **Healthcare-associated infection reduction**: By curtailing infection spread, microwave disinfection systems may reduce the substantial economic burden of healthcare-associated infections, though these indirect savings are challenging to quantify precisely.

The technology has proven particularly suitable for treating infectious waste, sharps after disintegration, and other non-

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71 Kishor Kalauni et al., "A comprehensive review of recycling and reusing methods for plastic waste focusing Indian scenario" *Waste management & research: the journal of the International Solid Wastes and Public Cleansing Association, ISWA* 734242X241308499 (2025).

72 "Plasma Pyrolysis Technology for Safe Disposal of Biomedical Waste,"*available at*: http://www.plasmaindia.com/Pyrolysis.html (last visited August 10, 2024).

73 Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

74 "Treating Medical Waste with Microwaves, and Irradiation,"*available at*: https://www.malsparo.com/treat2.htm (last visited August 10, 2024).

75 *Ibid.*

76 *Ibid.*

anatomical biomedical waste streams that constitute the majority of waste generated in most healthcare settings[77]. Its demonstrated effectiveness in achieving the 4-log (99.99%) bacterial reduction standard for Bacillus subtilis spores ensures regulatory compliance while maintaining economic viability[78].

Optimized Common Biomedical Waste Treatment Facilities

The centralized treatment model embodied in Common Bio-Medical Waste Treatment Facilities (CBMWTFs) offers significant cost advantages through economies of scale when properly optimized. India currently operates 198 such facilities with 28 more under construction, yet geographical coverage remains insufficient to serve all healthcare institutions within the prescribed 75-kilometer radius[79].

Economic modeling and multi-criteria decision analysis approaches have demonstrated that optimal CBMWTF planning can substantially enhance cost-effectiveness[80]. Key factors include:

1. **Strategic facility siting**: Multi-objective optimization models can identify optimal locations for waste collection sites, balancing transportation costs against facility establishment expenses while considering both prioritized large collection sites and common collection sites[81].
2. **Route optimization**: Efficient transportation routing reduces fuel consumption, vehicle maintenance, and labor costs while minimizing environmental impacts.
3. **Technology combination**: CBMWTFs can implement complementary treatment technologies optimized for different waste streams, achieving better overall performance than single-technology approaches typically feasible at individual healthcare facilities.
4. **Shared infrastructure costs**: Centralized facilities distribute capital costs across multiple healthcare institutions, making advanced technologies economically viable when they would be prohibitively expensive for individual facilities.

The economic viability of the CBMWTF model depends significantly on establishing appropriate service fees that balance affordability for healthcare facilities against operational sustainability for the treatment facility. Inadequate pricing models have contributed to financial challenges for many CBMWTFs in India, highlighting the need for economically sound planning that considers regional economic factor[82].

Bioremediation Approaches

Bioremediation technologies offer promising cost-effective solutions for certain biomedical waste streams, particularly those with high organic content. These approaches leverage natural biological processes to degrade or transform hazardous components, typically requiring lower capital investment and operational expenses than mechanical or thermal alternatives[83].

Key economic advantages include:

1. **Minimal infrastructure requirements**: Many bioremediation approaches require relatively simple containment systems rather than sophisticated mechanical equipment, reducing capital costs substantially.
2. **Low energy consumption**: Biological processes operate at ambient temperatures without requiring external energy inputs for heating or pressure generation, minimizing utility expenses.

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[77] *Ibid.*
[78] *Ibid.*
[79] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).
[80] Chaozhong Xue et al., "Design of the Reverse Logistics System for Medical Waste Recycling Part I: System Architecture and Disposal Site Selection Algorithm" (arXiv, 2023).
[81] *Ibid.*
[82] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).
[83] Mohd Sajjad Ahmad Khan, "Applications of Bioremediation in Biomedical Waste Management: Current and Future Prospects," 67 *Brazilian Archives of Biology and Technology* e24230161 (2024).

3. **Reduced chemical inputs**: Bioremediation primarily utilizes naturally occurring organisms rather than chemical reagents, eliminating costs associated with chemical procurement, handling, and storage.
4. **Minimal specialized training needs**: Once established, many bioremediation systems require basic monitoring rather than specialized technical expertise, reducing personnel costs.

Techniques like hydro-biodegradation and oxo-biodegradation of polymers, followed by photo-degradation and chemical degradation, show particular promise for addressing plastic components of biomedical waste[84]. Similarly, phytoremediation employing plants and rhizospheric microorganisms offers potential for remediating various pollutants present in hospital wastes, including radioactive materials, in a sustainable and economical manner[85].

However, bioremediation approaches typically operate more slowly than mechanical or thermal alternatives and may not achieve the same level of pathogen inactivation for highly infectious materials. Consequently, they are most cost-effective when integrated into comprehensive waste management systems rather than deployed as standalone solutions, particularly for treating pre-processed waste or specific waste fractions[86].

Localized Technological Solutions

Addressing India's diverse healthcare landscape requires recognizing that no single technology will prove optimal across all contexts. Studies evaluating waste-to-energy technologies' technological and economic viability for investment in India have demonstrated that different approaches demonstrate optimal performance under different operational scales and regional conditions[87].

Using the Complex Proportional Assessment (COPRAS) methodology to evaluate pyrolysis, gasification, plasma arc gasification, and anaerobic digestion technologies reveals that annual energy production and initial investment represent the most significant technical and economic factors influencing technology selection[88]. This analysis suggests that gasification and anaerobic digestion may offer more favorable techno-economic returns for smaller-scale applications typical in many Indian healthcare settings[89].

For remote rural healthcare facilities with limited resources and waste volumes, modular and scalable technologies that can be appropriately sized offer the most economically viable solution. Mobile treatment units utilizing microwave technology represent one such approach, enabling shared resources across multiple small facilities while eliminating long-distance waste transportation requirements[90].

Computer vision approaches for assisted primary sorting of medical waste offer another emerging cost-effective solution, potentially reducing labor costs while improving segregation accuracy[91]. By optimizing waste segregation at source, these systems can enhance the performance of subsequent treatment processes regardless of the specific technology employed, improving overall system cost-effectiveness[92].

Indian Approach Towards the Issue

India has developed a distinctive approach to biomedical waste management shaped by its unique healthcare landscape, regulatory framework, socioeconomic realities, and environmental challenges. This section examines the evolution of India's approach and assesses current strategies and initiatives.

Regulatory Evolution

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84 *Ibid.*
85 *Ibid.*
86 *Ibid.*
87 "Waste-to-energy technologies' technological and economic viability for investment in India: A COPRAS Method," 1 *Recent trends in Management and Commerce* 153–60 (2020).
88 *Ibid.*
89 *Ibid.*
90 "Treating Medical Waste with Microwaves, and Irradiation,"*available at*: https://www.malsparo.com/treat2.htm (last visited August 10, 2024).
91 A. Bruno et al., "Medical Waste Sorting: a computer vision approach for assisted primary sorting" (arXiv, 2023).
92 *Ibid.*

India's regulatory framework for biomedical waste management has undergone significant evolution over the past three decades. The country was among the first to initiate comprehensive measures for safe disposal of biomedical waste, with the Ministry of Environment and Forests notifying the first Biomedical Waste (Management and Handling) Rules in July 1998[93]. These initial regulations established basic frameworks for waste categorization, segregation, and disposal, but implementation remained challenging across much of the country.

In 2016, the Ministry of Environment, Forest and Climate Change notified the new Biomedical Waste Management Rules, replacing the earlier 1998 regulations[94]. These revised rules introduced several significant changes:

1. **Expanded scope**: The rules extended beyond hospitals and nursing homes to cover all persons generating biomedical waste, including vaccination camps, blood donation camps, surgical camps, and laboratories.
2. **Pre-treatment requirements**: The rules mandated that laboratory and highly infectious waste be pre-treated on-site before being sent for final disposal through common facilities.
3. **Bar-code system**: Introduction of bar-code labeling for all color-coded bags or containers to improve tracking and accountability.
4. **Phase-out of hazardous materials**: Mandated phasing out of chlorinated plastic bags, gloves, and blood bags (excluding blood bags) by March 27, 2019.
5. **Technology approvals**: Established processes for evaluating and approving new technologies for biomedical waste treatment[95].
6. **Stringent emission standards**: Introduced more rigorous emission norms for incinerators and specified advanced air pollution control devices[96].

Further amendments have been introduced subsequently to address emerging challenges and incorporate technological advancements. Despite these comprehensive regulations, implementation gaps remain significant across many healthcare facilities, particularly in rural and resource-constrained settings[97].

Institutional Framework

India has established a multi-tiered institutional structure for biomedical waste management oversight. The Central Pollution Control Board (CPCB) serves as the apex regulatory body at the national level, responsible for establishing standards, approving technologies, and providing technical guidance[98]. State Pollution Control Boards (SPCBs) and Pollution Control Committees (PCCs) in Union Territories implement and enforce regulations at the state leve[99].

Healthcare facilities are required to establish institutional biomedical waste management committees responsible for developing and implementing waste management policies and protocols. Regular monitoring and reporting structures have been established, with healthcare facilities mandated to submit annual reports to regulatory authorities.

Common Bio-Medical Waste Treatment Facilities (CBMWTFs) represent a key institutional innovation in India's approach. These centralized facilities serve multiple healthcare institutions within a defined geographical area, enabling economies of scale and specialized expertise that would be impractical for individual facilities to maintain. The BMWM

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93 Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

94 *Ibid.*

95 "CPCB | Central Pollution Control Board,"*available at*: https://cpcb.nic.in/states-of-new-technologies-for-treatment-disposal-of-bmw/ (last visited August 10, 2024).

96 Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016

97 Yuvappreya Krishnamurthy et al., "Predictors of biomedical waste management practices among staff nurses of a tertiary care teaching hospital in India," 13 *Journal of Education and Health Promotion* 78 (2024).

98 Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).

99 Central Pollution Controal Board Guideline for Management of Healthcare Waste as per Biomedical Waste Management Rules,2016

Rules explicitly promote this model by stipulating that healthcare facilities should not establish on-site treatment facilities if a CBMWTF is available within 75 kilometers[5].

Technology Evaluation and Approval

India has established formal processes for evaluating and approving alternative technologies for biomedical waste management. The Central Pollution Control Board assesses innovative waste treatment methods and may grant conditional or provisional approval for technologies not explicitly covered under the BMWM Rules[100].

Between 2010 and 2013, the CPCB granted conditional or provisional approval to several new technologies including plasma pyrolysis, waste sharps dry heat sterilization and encapsulation, sharp blaster (needle blaster), and PIWS-3000 technology[101]. This formal evaluation process provides a pathway for technological innovation while ensuring that alternative methods meet essential performance and safety standards.

Notably, plasma pyrolysis has received official recognition as an approved method for treating certain categories of biomedical waste, particularly anatomical waste where incineration would otherwise be required. Similarly, microwave-based systems have gained regulatory acceptance and widespread implementation, including in prestigious institutions such as AIIMS.

Implementation Challenges

Despite comprehensive regulations and institutional frameworks, India faces significant challenges in implementing effective biomedical waste management practices across its diverse healthcare landscape. Studies consistently identify several persistent barriers:

1. **Knowledge and practice gaps**: Research across various healthcare settings reveals substantial discrepancies between awareness of proper protocols and actual practices. A study in a tertiary care hospital found that despite training, compliance with waste segregation protocols was initially only 57%, though this improved to 91% following targeted interventions[2]. Similar studies in primary health centers in Sikkim found that while 66% of healthcare workers possessed adequate knowledge, only 60% demonstrated good practice scores[102].
2. **Infrastructure limitations**: Many healthcare facilities lack the basic infrastructure required for proper waste segregation, temporary storage, and safe handling. The distribution of CBMWTFs remains insufficient, with many healthcare institutions located beyond the prescribed 75-kilometer radius from the nearest facility[103].
3. **Financial constraints**: Resource limitations present significant barriers, particularly for public healthcare facilities and smaller institutions. The costs of implementing bar-code systems, phasing out chlorinated plastics, and establishing appropriate waste management infrastructure often exceed available budgets.
4. **Training deficiencies**: Studies consistently identify inadequate training as a major factor limiting effective waste management, particularly among supportive medical staff and waste handlers who often receive less formal education on these topics than medical professionals[104].
5. **Monitoring and enforcement challenges**: Limited regulatory capacity for monitoring and enforcing compliance has contributed to implementation gaps, with many facilities continuing non-compliant practices without consequences[105].

[100] "CPCB | Central Pollution Control Board," *available at*: https://cpcb.nic.in/states-of-new-technologies-for-treatment-disposal-of-bmw/ (last visited August 10, 2024).
[101] *Ibid.*
[102] Sunita Thapa and Nasrin B. Laskar, "Biomedical waste management among healthcare workers in a Primary Health Centre in Sikkim, India—A KAP study," 13 *Journal of Education and Health Promotion* 378 (2024).
[103] Priya Datta, Gursimran Mohi and Jagdish Chander, "Biomedical waste management in India: Critical appraisal," 10 *Journal of Laboratory Physicians* 006–14 (2018).
[104] A. Bruno et al., "Medical Waste Sorting: a computer vision approach for assisted primary sorting" (arXiv, 2023).
[105] Komal S Dhole et al., "Navigating Challenges in Biomedical Waste Management in India: A Narrative Review," 16 *Cureus* e55409.

Indigenous Technology Development

A distinctive aspect of India's approach has been emphasis on developing indigenous technologies tailored to local conditions. The OptiMaser microwave-based system, described as "designed, developed and patented by Govt. of India," exemplifies this focus on homegrown solutions. Similarly, the innovation of graphite torch technology for plasma pyrolysis at the Facilitation Centre for Industrial Plasma Technologies demonstrates India's capabilities in adapting and enhancing technologies for local conditions[106].

Indigenous technology development offers several advantages, including lower implementation costs, designs appropriate for local infrastructure realities, and reduced dependence on imported equipment and expertise. These developments also position India as a potential exporter of biomedical waste management technologies to other developing nations facing similar challenges.

Public-Private Partnerships

India has increasingly embraced public-private partnership models for biomedical waste management, particularly in establishing and operating CBMWTFs. These arrangements leverage private sector efficiency and capital while maintaining public oversight of essential health and environmental functions.

The government has worked to create enabling environments for private investment in waste management infrastructure through policies including tax incentives, streamlined approval processes, and guaranteed waste volumes from public healthcare facilities. However, challenges remain in establishing economically sustainable models, particularly for serving smaller healthcare facilities and those in remote areas where operational costs may exceed revenue potential.

Conclusion and Suggestions

Biomedical waste management in India stands at a critical juncture, with growing recognition of environmental and public health implications driving the search for sustainable alternative technologies. This comprehensive review has examined existing practices, emerging technologies, and the unique challenges and opportunities within the Indian context. Several key conclusions emerge from this analysis.

Key Findings

The current biomedical waste management landscape in India reveals significant achievements alongside persistent challenges. The country has established a comprehensive regulatory framework through the Biomedical Waste Management Rules of 2016 and subsequent amendments, creating clear guidelines for waste categorization, segregation, treatment, and disposal. The development of 198 Common Bio-Medical Waste Treatment Facilities with 28 more under construction represents substantial progress toward establishing necessary infrastructure.

However, implementation gaps remain pronounced across many healthcare settings. Studies consistently demonstrate discrepancies between knowledge and practice among healthcare workers, with compliance rates for proper waste segregation ranging from 57% to 91% even in tertiary care facilities[107]. Infrastructure limitations, financial constraints, inadequate training, and monitoring challenges continue to impede effective implementation of regulations across much of the country.

Alternative technologies show considerable promise for addressing the limitations of conventional biomedical waste management approaches. Plasma pyrolysis offers environmental advantages through operation in oxygen-starved environments that minimize toxic emissions, with Indian innovations like the graphite torch system enhancing energy efficiency by 35%[108]. Microwave-based systems like OptiMaser demonstrate cost-effectiveness through minimal operational expenses and automation features that reduce labor requirements while ensuring effective pathogen

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[106] The Indian Practitioner, "Plasma Pyrolysis of Bio-medical Waste" *The Indian Practitioner*, 2022*available at*: https://theindianpractitioner.com/plasma-pyrolysis-of-bio-medical-waste/ (last visited August 10, 2024).
[107] Yuvappreya Krishnamurthy et al., "Predictors of biomedical waste management practices among staff nurses of a tertiary care teaching hospital in India," 13 *Journal of Education and Health Promotion* 78 (2024).
[108] The Indian Practitioner, "Plasma Pyrolysis of Bio-medical Waste" *The Indian Practitioner*, 2022*available at*: https://theindianpractitioner.com/plasma-pyrolysis-of-bio-medical-waste/ (last visited August 10, 2024).

inactivation[109].

Electron beam technology has demonstrated effectiveness for hospital wastewater treatment, achieving significant reductions in chemical oxygen demand, pathogenic bacteria, and various viruses without generating harmful byproducts[110]. Bioremediation approaches offer environmentally harmonious and economically accessible options for certain waste streams, particularly those with high organic content[111]. Computer vision approaches for assisted waste sorting represent emerging solutions for improving segregation accuracy and efficiency[112].

Economic considerations remain central to technology selection and implementation strategies. Initial capital costs often present barriers to adopting advanced technologies, particularly for smaller healthcare facilities and those in resource-constrained settings[113]. However, operational savings, reduced environmental impacts, and health benefits may justify these investments when properly quantified through comprehensive economic analysis.

Recommendations

Based on the findings of this review, several recommendations emerge for enhancing biomedical waste management in India through alternative technologies:

1. **Strengthen Regulatory Enforcement**: While India has established comprehensive regulations, implementation remains inconsistent. Enhancing monitoring capacity, introducing more effective compliance incentives, and implementing graduated penalty structures could improve adherence to existing regulations without imposing excessive burdens on healthcare facilities.
2. **Develop Tailored Technology Solutions**: Recognizing India's diverse healthcare landscape, from sophisticated urban hospitals to resource-constrained rural facilities, requires developing and promoting a spectrum of technological solutions appropriate for different operational scales and resource availabilities. Modular, scalable technologies that can be appropriately sized for smaller facilities merit particular attention.
3. **Enhance Public-Private Partnerships**: Expanding and optimizing public-private partnership models could accelerate infrastructure development while ensuring economic sustainability. Performance-based contracting, risk-sharing mechanisms, and innovative financing approaches could help overcome the financial barriers currently limiting CBMWTF coverage.
4. **Invest in Training and Capacity Building**: Studies consistently identify knowledge-practice gaps as significant barriers to effective waste management. Comprehensive training programs targeting all categories of healthcare workers, particularly supportive staff and waste handlers, could substantially improve compliance with proper protocols even without technological upgrades.
5. **Prioritize Indigenous Technology Development**: Continued investment in developing and refining homegrown technologies like the OptiMaser system and innovative plasma pyrolysis approaches would reduce dependency on imported solutions while ensuring appropriateness for local conditions. Establishing technology incubation centers focused specifically on biomedical waste management could accelerate innovation in this sector.
6. **Implement Life Cycle Assessment Approaches**: When evaluating alternative technologies, comprehensive life cycle assessment methodologies should be employed to ensure that environmental benefits are not offset by

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109 "Treating Medical Waste with Microwaves, and Irradiation,"*available at*: https://www.malsparo.com/treat2.htm (last visited August 10, 2024).

110 "Treatment of hospital wastewater by electron beam technology: Removal of COD, pathogenic bacteria and viruses - PubMed,"*available at*: https://pubmed.ncbi.nlm.nih.gov/36055595/ (last visited August 10, 2024).

111 Mohd Sajjad Ahmad Khan, "Applications of Bioremediation in Biomedical Waste Management: Current and Future Prospects," 67 *Brazilian Archives of Biology and Technology* e24230161 (2024).

112 A. Bruno et al., "Medical Waste Sorting: a computer vision approach for assisted primary sorting" (arXiv, 2023).

113 "Waste-to-energy technologies' technological and economic viability for investment in India: A COPRAS Method," 1 *Recent trends in Management and Commerce* 153–60 (2020).

unintended consequences elsewhere in the product life cycle. This approach would provide more accurate comparisons between competing technologies and prevent potential problem-shifting.

7. **Establish Regional Knowledge Centers**: Creating regional centers of excellence for biomedical waste management could facilitate knowledge transfer, provide technical assistance to healthcare facilities, and serve as demonstration sites for alternative technologies. These centers could offer training, conduct applied research, and provide advisory services to healthcare facilities within their regions.
8. **Develop Financial Incentive Structures**: Innovative financial mechanisms, including subsidies for environmentally superior technologies, tax incentives for early adopters, and preferential financing for waste management infrastructure, could help overcome the economic barriers currently limiting technology adoption, particularly among smaller healthcare facilities.

Future Research Directions

This review identifies several promising areas for future research to advance biomedical waste management in India:

1. **Technology Optimization**: Further research is needed to optimize alternative technologies for Indian conditions, including developing lower-cost versions of plasma pyrolysis systems, enhancing microwave treatment efficiency, and adapting electron beam technology for broader application.
2. **Economic Modeling**: More sophisticated economic analysis incorporating direct and indirect benefits of improved waste management, including reduced healthcare-associated infections, environmental remediation avoidance, and potential resource recovery, would provide more accurate assessments of alternative technologies' cost-effectiveness.
3. **Integration Approaches**: Research exploring optimal combinations of complementary technologies to address diverse waste streams could yield more effective comprehensive solutions than single-technology approaches. Particularly promising is the integration of biological methods with physical and thermal technologies to create hybrid systems.
4. **Behavioral Studies**: Understanding the social, cultural, and organizational factors influencing waste management behaviors among healthcare workers would enable more effective interventions to bridge the persistent knowledge-practice gap identified across multiple studies.
5. **Decentralized Solutions**: Given the geographical dispersion of healthcare facilities in India, research on effective decentralized treatment options for remote and rural areas beyond the reach of centralized facilities could significantly enhance overall waste management performance.

In conclusion, effective biomedical waste management in India requires a multifaceted approach combining technological innovation, regulatory enforcement, capacity building, and economic incentives. Alternative technologies offer promising solutions to the environmental and operational challenges of conventional methods, but their successful implementation depends on addressing the complex interplay of technical, economic, social, and institutional factors shaping India's healthcare waste landscape. By pursuing the recommendations outlined above and investing in continued research and development, India can transform its approach to biomedical waste management, protecting public health and environmental integrity while establishing models that may benefit other developing nations facing similar challenges.