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Biomedical Waste Governance in BRICS: Comparative Policy Perspectives and SDG Integration

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Abstract. Biomedical waste poses significant risks to public health and the environment when not managed properly. While healthcare facilities (HCFs) are intended to heal, they also generate hazardous waste such as used syringes, sharps, and contaminated materials that can exacerbate environmental pollution if treated inadequately. In India, despite implementing the Biomedical Waste Management Rules, 2016, challenges persist due to systemic non-compliance, especially among unauthorized HCFs, and insufficient waste treatment infrastructure. Accordingly, this article employs a doctrinal and comparative policy approach to assess regulatory frameworks and implementation strategies across the BRICS countries. Using 2020 Central Pollution Control Board (CPCB) statistics, it examines India's biomedical waste management policy while drawing cross-jurisdictional insights from Brazil, Russia, China, and South Africa. The report finds major areas of policy convergence and divergence, particularly on regulatory design, public-private compliance mechanisms, and technology integration. Based on this comparative study, the article offers the Public-Private Compliance Incentive Model (PPCIM) and recommends regionally coordinated efforts to bridge regulatory and infrastructure gaps. By situating these proposals within the framework of the Sustainable Development Goals (SDGs), specifically 3, 6, 12, and 17, this article emphasises the critical role of BRICS collaboration in transforming biomedical waste management from a regulatory challenge to a catalyst for sustainable health and environmental governance.

Keywords: biomedical waste management; sustainable development goals; environmental governance; BRICS nations; cross-jurisdictional analysis; health and environmental justice; waste treatment technologies.

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Introduction

Among the many environmental concerns, biomedical waste has emerged as a uniquely complex threat due to its infectious and hazardous nature particularly in emerging economies like the BRICS.[1] This issue has become central to contemporary discourse, as the environment provides the fundamental elements for human survival, i.e., clean air, safe drinking water, and nutritious and pure food. A degraded environment can have serious consequences for human health, leading to respiratory disorders, neurological impairments, cancers, and other critical illnesses.[2] Beyond

[1] Praveen, K., Ganguly, S., & Wakchaure, R. (2017). Environmental pollution and safety measures: International issues and its global impact. In M. M. Abid Ali Khan et al. (Eds.), *Global progress in development of sustainable environment* (pp. 40–65). Discovery.

[2] Janik-Karpinska, E., et al. (2023). Healthcare Waste–A Serious Problem for Global Health. *Healthcare*, *11*(2), 242–256.

sustaining human life, the environment supports many plant and animal species integral to maintaining ecological balance.[3] Protecting the environment thus ensures the preservation of biodiversity and reduces the risk of species extinction. A healthy environment is also imperative for climate regulation and is a source of essential materials supporting agriculture, industry, and daily life.[4] However, human interventions–deforestation, industrial emissions, and the excessive use of fossil fuels–have contributed to severe environmental degradation. These activities have accelerated climate change, triggering phenomena such as rising sea levels, ocean acidification, and extreme weather events, all posing long-term threats to ecological stability and intergenerational sustainability.[5]

Among the many contributors to environmental degradation, the improper disposal of biomedical waste is a significant and often overlooked concern.[6] Biomedical waste generated during the diagnosis, treatment, or immunization of humans and animals includes used syringes, contaminated bandages, pharmaceutical residues, and discarded medical devices.[7] This waste is broadly categorized into infectious waste (e.g., blood-soaked materials, sharps), hazardous waste (e.g., chemical disinfectants, cytotoxic drugs), and radioactive waste (e.g., materials from radiation therapy and diagnostic procedures). Numerous studies have indicated that when biomedical waste is mishandled or inadequately disposed of, it poses serious risks to human health, animal life, and the environment.[8] Therefore, effective and sustainable biomedical waste management has become an urgent public health and environmental mandate, particularly in countries facing rapid population growth and expanding healthcare demands.[9] Given the severity of the risks associated with improper biomedical waste management, it is essential to have robust legal and regulatory mechanisms in place to ensure the safe handling,

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3 Nnawulezi, U., & Nwaechefu, H. (2022). Reinforcing indigenous peoples' right to health in the wake of the COVID-19 pandemic: A panacea for sustainable human rights protection. *BRICS Law Journal*, *9*(4), 108–133.

4 Aplet, G. H., & Mckinley, P. S. (2017). A portfolio approach to managing ecological risks of global change. *Ecosystem Health and Sustainability*, *3*(2), e01261.

5 Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, *151*(2), 362–367.

6 McMichael, A. (2003). *Climate change and human health: risks and responses*. World Health Organization. https://iris.who.int/server/api/core/bitstreams/6397f75e-4fee-4ebe-9842-213a47e82ca0/content

7 Divan, Sh., & Rosencranz, A. (2022). *Environmental law and policy in India: Cases and materials*. Oxford University Press.

8 Omo, Q. G., & Hassan, N. E. (2024). Biomedical waste management and their effects on the environment: A review. *World Journal of Advanced Engineering Technology and Sciences*, *11*(01), 86–95.

9 Rawcliffe, C. (2014). Sources for the study of public health in the medieval city. In J. T. Rosenthal (Ed.), *Understanding medieval primary sources: using historical sources to discover medieval Europe* (pp. 177–195). Routledge.

treatment, and disposal of such waste. The responsibility for mitigating these risks lies with healthcare facilities, governments, and regulatory authorities tasked with setting and enforcing biomedical waste standards. As in other BRICS nations, the legal framework is crucial in shaping biomedical waste management practices in India. Understanding these frameworks' effectiveness, limitations, and enforcement mechanisms is essential to identifying systemic gaps and formulating sustainable solutions. The following section critically examines the legal and regulatory landscape governing biomedical waste management in India, with comparative insights from other BRICS countries to evaluate the effectiveness of existing policies and the potential for cross-jurisdictional learning.

1. Legal & Regulatory Framework

Resilient regulatory and legal frameworks are essential for effectively managing biomedical waste. Among BRICS countries, the strength and enforceability of such regulations vary considerably.[10] While some nations have developed comprehensive legal systems, inconsistencies in implementation and regulatory loopholes remain key challenges. As a member of the BRICS bloc, India has made progress in formulating and enforcing biomedical waste management policies.[11] While its approach holds domestic significance and potential as a model for others, India must also proactively learn from the best practices of fellow BRICS nations.

The Government of India introduced the Biomedical Waste (Management and Handling) Rules, 1998, in July 1998 to address the growing concerns related to the improper disposal of biomedical waste.[12] These rules establish accountability among healthcare facilities (HCFs) and ensure the proper management and disposal of waste they generate.[13] Applicable to all HCFs such as hospitals, clinics, laboratories, and research institutions, the primary objectives of these rules were to promote environmentally sound waste management practices, safeguard the health of healthcare workers and waste handlers, and standardize procedures for segregation, collection, storage, transportation, and disposal of biomedical waste.[14] Additionally, the rules outlined the classification of biomedical waste types, introduced a color-coding system for waste containers, and specified labelling and packaging standards.

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10 Anisimov, A., & Ju, K. (2019). Trends and prospects for legislative regulation of legal responsibility for environmental offenses in BRICS countries: Comparative law. *BRICS Law Journal*, *6*(1), 82–101.

11 Datta, P., Mohi, G., & Chander, J. (2018). Biomedical waste management in India: Critical appraisal. *Journal of Laboratory Physicians*, *10*(1), 6–14.

12 Capoor, M. R., & Bhowmik, K. T. (2017). Current perspectives on biomedical waste management: Rules, conventions and treatment technologies. *Journal of Medical Microbiology*, *35*(2), 157–164.

13 Patil, A. D., & Shekdar, A. V. (2001). Healthcare waste management in India. *Journal of Environmental Management*, *63*(2), 211–220.

14 Singh, A., & Kaur, S. (2012). *Biomedical waste disposal*. Jaypee Brothers.

Additionally, healthcare facilities were also required to maintain detailed waste generation, collection, and disposal records and submit regular reports to the designated authorities.

In response to evolving challenges and gaps in the 1998 regulations, the Government of India introduced a revised and more robust framework, the Biomedical Waste Management Rules, 2016. These rules were legislated by the powers conferred on the central government under the Environment (Protection) Act, 1986. The new set of exhaustive rules aims to streamline and increase the efficacy of managing and administering biomedical waste generated in the country and address the emerging challenges and developments in the field.[15] Any stakeholder directly involved in generating, collecting, preserving, conveying, treating, or disposing of biomedical waste must now abide by these regulations.[16] In reference to waste collection, the 2016 rules mandate segregation into four systematic categories instead of the earlier ten categories under the 1998 rules, while entailing the appropriate color-coding system (*see* Figure 1). The new rules allow for the pre-treatment of laboratory waste to reduce its volume and ensure safe disposal, and mandate that every waste container have a barcoding system to track the waste from its generation to disposal.[17] Hence, they emphasize the need for a sustainable and environmentally friendly approach towards waste management while promoting the safety and scientific disposal of biomedical waste to prevent adverse impacts on the health of the species and the environment.

These rules are comprehensive and enforceable, requiring each healthcare facility to categorize waste using standardized colour codes (*see* Figure 1).[18] The segregated waste can be stored for up to two days before being properly disposed of or picked up by a professional from a facility that handles typical bio-medical waste, i.e., Common Biomedical Waste Treatment Facility (CBMWTF). The CMBWTF then treats the waste according to the color of the bag. A few of these disposal techniques are deep entombment, cremation, autoclaving, annihilation, chemical treatment, and transportation to secured landfills or wastelands.[19] In certain instances, the concerned healthcare institutions are de-facto in charge of pre-treating blood tests, blood bags,

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15 Goswami, M., Goswami, P. J., Nautiyal, S., & Prakash, S. (2021). Challenges and actions to the environmental management of bio-medical waste during COVID-19 pandemic in India. *Heliyon*, *7*(3), e06313.

16 Datta, Mohi & Chander, 2018.

17 Maurya, S., Saxena, A., Srivastava, K., Singh, A., Joshi, R., & Patel, A. (2025). Strategies for bio-medical waste management: A comprehensive approach. In A. Mandpe, S. Paliya & M. P. Shah (Eds.), *A vision for environmental sustainability: Overcoming waste management challenges in developing countries* (pp. 167–190). Springer.

18 Babu, R., et al. (2009). Management of biomedical waste in India and other countries: A review. *Journal of International Environmental Application & Science*, *4*(1), 65–78.

19 Hajam, Y. A., & Lata, P. (2025). Management of biomedical wastes. In *Biomedical Waste Management* (p. 85). Apple Academic Press.

and microbiological waste which is generated from their facilities through local sanitization and eviscerating following the recommendations made by National Aids Control Organization (NACO) and World Health Organization (WHO), even though these HCFs rely on CBMWTF or have in-house captive facility for treating the waste. Finally, healthcare facilities are further suggested to stop employing the chlorinated plastic bags, medicated gloves, and packs containing blood to prevent the emission of dioxins and furans from burning such trash.[20] Nevertheless, the efficacy of these rules is limited by structural enforcement deficits, such as capacity gaps in State Pollution Control Boards and insufficient digital compliance monitoring. Unlike China's real-time tracking or Brazil's fiscal compliance models, India's enforcement remains reactive rather than proactive.

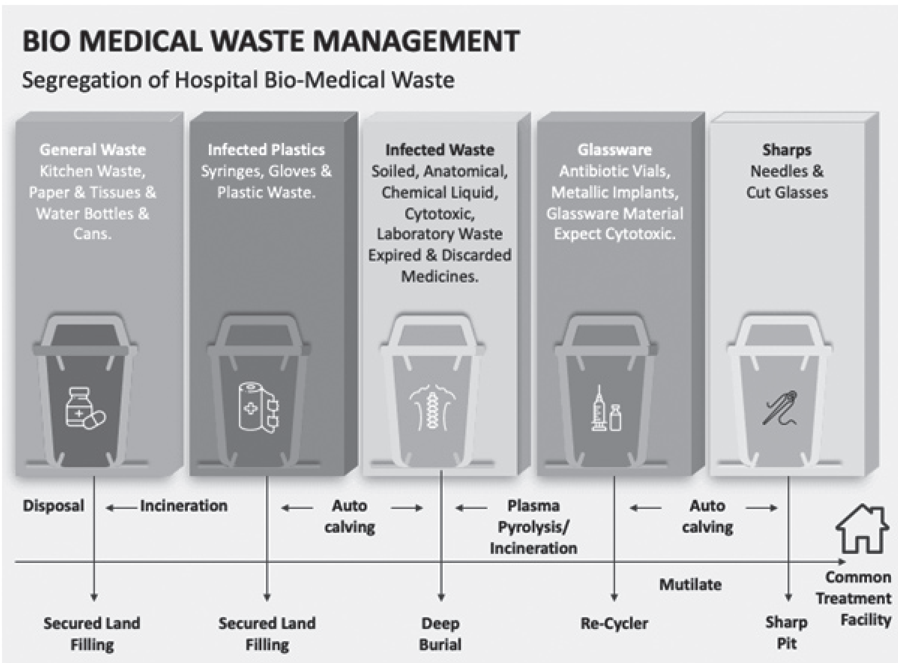

Figure 1: **Color Coding of Bio-Medical Waste**[21]

[20] Wisniewski, A., Zimmerman, M., Crews, T., Haulbrook, A., Fitzgerald, D. C., & Sistino, J. J. (2020). Reducing the impact of perfusion medical waste on the environment. *Journal of Extra Corporeal Technology*, *52*(2), 135–141.

[21] Biomedical Waste Management. (2022, April). *Role of Hospitals*. Clutch Health, https://clutch-health.in/biomedical-wastebmw-management-role-of-hospitals

1.1. Initiatives by States

In order to mitigate the harmful effects on public health and the environment, Common Biomedical Waste Treatment Facilities (CBWTFs) were established in various districts of the states. Herein, the biomedical waste generated by its healthcare facilities has been appropriately treated. After treatment, recyclable material can either be recycled or disposed of in secure landfills or wastelands. Healthcare facilities located within a 75-km radius of a CBWTF are generally restricted from setting up their treatment facilities, as per the 2016 regulations.[22] According to the revelations in Annual Reports on BMW, currently, 208 CBWTFs are operational in the country, and almost 30 are under construction. A few North Eastern States, along with Goa and Andaman & Nicobar, do not have the CBWTFs for treating and disposing of biomedical waste. However, if the CBWTF is unavailable, the Healthcare Facilities may establish their treatment facility per the requirements in the aforementioned Regulations for treating and disposing of biological waste. Under this proviso, almost 17,206 healthcare facilities have installed their respective captive facilities, wherein the State's pollution control boards were instructed to oversee adherence to the 2016 Biomedical Waste Management Regulations. In case of any violation, the concerned HCFs can be ordered to shut down their facility and, thereafter, be compelled to become members of CBWTF. Some of these captive treatment facilities also offer deep burial facilities, whose condition must be regularly monitored by the State's pollution control bodies.[23]

Further, the regulations also mandate each operator of the shared bio-medical waste treatment facility to install an Online Continuous Emission Monitoring System (OCEMS) in order to monitor the treatment of waste in real-time for the parameters as stipulated by State Pollution Control Boards (SPCB) or Central Pollution Control Board (CPCB) in transmitting and authorizing the real-time data to their servers. According to the statistics provided, of the total operation CBWTFs, only 93.75% have followed this instruction of installing OCEMS with their incineration stack.

2. Compliance and Findings

According to the new rules of 2016, every year, by July 31, the SPCB of each State is obligated to submit an annual report. This report must include information and minutes about the collection, handling, transportation, and disposal of biomedical waste in the respective State. The report is directed to the Ministry of Environment, Forests & Climate Change (MoEFCC) for further collation of the data received from other states. Despite regulatory mandates, compliance remains inconsistent. The

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[22] Baghotia, K. S. (2017). Systems approach in biomedical waste management. *Journal of Indian Society of Hospital Waste Management*, *16*(1), 36–73.

[23] Central Pollution Control Board (2020).

2020 CPCB report illustrates this through alarming statistics (*see* Table 1). According to this report, the cumulative quantum of biomedical waste generated by each State was reported as 774 tonnes per day, of which almost 8.53% of waste was not treated. Of the total waste collected, 656 tonnes per day was non-COVID and 118 tonnes per day was COVID-related biomedical waste.

As a consequence, an unaccounted portion of bio-medical waste (including COVID) must have been disposed of in the environment or landfills. Furthermore, of the total 352,014 operational HCFs, only 69% are authorized HCFs, and accordingly receive assistance for the collection, transportation, treatment, and disposal of BMW. While 5% of HCFs have their captive waste treatment facilities, which deal with the disposal and treatment of waste. This annual report has revealed a few discrepancies and non-compliances with a few provisions of BMW Rule 2016, such as the lack of liquid waste pre-treatment facilities, the failure to disclose the existence of deep burial trenches, and the more alarming problem of an unauthorized healthcare facility. The report further revealed that out of the total operational HCFs in India, almost 54.33% of HCFs are unauthorized. Additionally, around 22,261 HCFs were reported to have violated the BMW Rule 2016, of which only 60% were issued show-cause notices concerning the respective violation.[24]

Table 1: **Data related to HCFs, generation, and treatment of Biomedical Waste**[25]

S No.	Particulars	Data	Remarks
I	Number of Operational Healthcare Facilities	3,52,014	–
II	Number of Authorized HCFs	1,60,736	45.66% of I
III	Number of Unauthorized HCFs	1,91,278	54.33% of I
IV	HCFs using CBMWTF	2,44,282	69.39% of I
V	HCFs have their own captive BMW Management facility	17,206	4.88% of I
VI	Bio-Medical Waste Generation	774 tons/day	–
VII	Non-COVID-19 Bio-Medical Waste Generated	656 tons /day	84.75% of VI
VIII	COVID-Related Bio-Medical Waste Generated	118 tons/day	15.25% of VI
IX	Bio-Medical Waste Treated by CBMWTF & Captive facilities	708 tons/day	91.47%

24 Central Pollution Control Board (2020).

25 Central Pollution Control Board (2022).

X	Bio-Medical waste untreated	66 tons/day	8.53%
XI	HCFs in violation of BMW Rules	22,261	6.32% of I
XII	HCFs received a show-cause notice from SPCB for violation of BMW Rules	13,389	60.14% of XI

By observing this dataset, there are various gaps in ensuring full compliance with the rules concerning effective management of Bio-Medical Waste. A regression in compliance from 2018 to 2020 highlights not merely institutional inefficiency but systemic tolerance for non-compliance. This has long-term consequences for water pollution and zoonotic outbreaks, particularly in high-density urban regions. Meanwhile, the key concerns that require immediate intervention are mentioned herein:

(i) Unauthorized healthcare facilities are not subject to mandatory compliance with the rules. Thus, they are not bound to report their biomedical waste generation to the concerned CBWTF. Hence, the waste generated by these HCFs remains unaccounted and may be disposed of untreated in landfills or wastelands.

(ii) Almost 25.73% of HCFs do not have their own captive BMW management facility, nor do they rely on a CBWTF. Hence, the waste generated by these HCFs is also unaccounted for and may be left untreated.

(iii) Approximately 66 tons per day, or 792 tons per year, of generated bio-medical waste is left untreated. This waste includes COVID waste. Subsequently, this waste may be disposed of in wastelands, water bodies, or garbage dumps.

(iv) Almost 40% of the HCFs that have violated some or other provisions of BMW Rules 2016 have not received any show-cause notice by the State's pollution control board. It reflects the concerns related to the implementation and execution of penal provisions.

3. Technological Inclusion

Technology plays a pivotal role in modernizing biomedical waste management. An improper technique of garbage disposal eventually arises from improper segregation. The waste generated by the HCFs is mixed with common garbage due to improper segregation techniques, making the entire waste stream dangerous. Besides that, an inadequate management of such wastes also results in environmental pollution and proliferation of pests like insects and rodents, leading to the spread of diseases like cholera, typhoid, hepatitis, and serious infections such as AIDS, which can originate from syringes and needles contaminated with human blood.[26] Subsequently, HCFs administration and regulatory bodies such as Pollution Control Boards (PCBs) should

[26] Price-Smith, A. T. (Ed.). (2001). *Plagues and politics: infectious disease and international policy*. Springer.

look for novel, scientific, safe, and economical ways to manage the trash, and keep the direct stakeholders, such as Doctors, Nurses, Lab Technicians, Diagnostics, and Rag Pickers, updated on the latest developments in this field. Nevertheless, some traditional techniques must be adopted by the HCFs to reduce the generation of and improve biomedical waste management. They can commence by adopting a waste reduction plan focusing on reducing waste generation at the source. It may include implementing a green purchasing policy, reducing packaging waste, and using reusable medical devices. Establishing the procedures of appropriate waste segregation can help reduce the amount of biomedical waste generated. It involves separating infectious waste, sharps, pharmaceutical waste, and other types of waste into separate containers for disposal or recycling. Then there is a need to implement a recycling program for paper, cardboard, plastic, and glass items. It can help reduce the volume of waste dumped in landfills and provide basic training to hospital staff on appropriate procedures for managing the generated waste. Apart from relying only on the traditional methods, the State shall persuade the PCBs and HCFs to adopt technologically advanced protocols and methods to reduce, segregate, and treat the hazardous wastes. Some of these technologies are mentioned herein and compared in Table 2.

3.1. Incineration Technology

Incineration is a high-temperature waste treatment procedure (800–1000°C) that can process a wide range of waste types, including biomedical and hazardous waste. It minimizes waste volume by up to 90%, making it very effective in space-constrained environments. Its ability to neutralise pathogenic and poisonous chemicals improves environmental safety, while its potential for energy recovery (by steam or electricity) increases its sustainability worth. However, the technique produces pollutants like greenhouse gases and harmful particles, which raises environmental concerns. Furthermore, its high installation and maintenance costs make it unfeasible in resource-constrained environments such as many districts of India, emphasising the need for cost-effective alternatives or hybrid solutions.[27]

3.2. Non-Incineration Technologies

Mechanical-Biological Treatment (MBT) is a non-combustion waste management strategy that combines mechanical sorting with biological processes like composting or anaerobic digestion. It is very successful in treating organic and mixed municipal garbage, reducing landfill dependence and enabling resource recovery. MBT requires less capital than incineration and produces fewer pollutants, making it more appropriate for developing countries. However, its efficiency is dependent on

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[27] Cogut, A. (2016). *Open burning of waste: A global health disaster*. https://api.semanticscholar.org/CorpusID:202548765

efficient waste segregation at the source, and it may require other technologies to effectively manage leftover hazardous components.

3.3. Chemical Technology

It involves the use of chemical agents to treat waste. The process can neutralize hazardous waste, separate metals from other waste materials, or reduce the volume of waste.[28]

3.4. Pyrolysis

Pyrolysis is a thermal waste treatment process that decomposes organic materials in the absence of oxygen, producing gas, oil, and charcoal. It provides a sustainable way to manage biomedical and organic waste while also producing biofuels, which contributes to circular economy aims. Pyrolysis has fewer emissions than incineration and can be used for decentralised waste treatment. However, the technology necessitates precise operational controls and a hefty initial investment, which may limit its widespread adoption in low-resource environments unless supported by public-private partnerships and long-term policy incentives.[29]

3.5. Plasma Gasification

It involves the use of high-temperature plasma to convert waste into a gas that can be used to produce energy. This process can be used to handle a wide variety of wastes.[30]

3.6. Autoclaving

Autoclaving is also referred to as steam sterilization, the procedure adopted to sterilize medical waste, including infectious waste and laboratory materials. It involves using high-pressure steam to kill microorganisms that may be present in the waste. During the process, the waste is placed in a sealed chamber, and steam is introduced at a high pressure and temperature (usually between 121–134 degrees Celsius). The heat and pressure cause the microorganisms to break down, effectively sterilizing the waste. Autoclaving has been proven to be highly effective at sterilizing medical waste, reducing the risk of infection and contamination. It produces no harmful emissions or by-products, making it a more environmentally friendly waste management option than incineration. The technique is often less expensive than

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[28] Demirbas, A. (2011). Waste management, waste resource facilities and conversion processes. *Energy Conversion and Management*, *52*(2), 1280–1287.

[29] Hsu, E., Barmak, K., West, A. C., & Park, A. A. (2019). Advancements in the treatment and processing of electronic waste with sustainability: A review of metal extraction and recovery technologies. *Green Chemistry*, *21*(5), 919–936.

[30] Fabry, F., Rehmet, C., Rohani, V., & Fulcheri, L. (2013). Waste gasification by thermal plasma: A review. *Waste and Biomass Valorization*, *4*, 421–439.

incineration or other waste treatment options, making it more accessible to smaller healthcare facilities or clinics. Whereas autoclaving equipment requires regular maintenance and calibration to ensure that it is functioning correctly, the process requires significant energy to heat the steam and maintain the high pressure, making it less energy-efficient than other waste treatment options.[31]

3.7. Microwave Irradiation

A technology used to treat medical waste involves exposing the waste to microwave radiation. This technology uses high-frequency electromagnetic waves to generate heat, killing microorganisms and sterilizing waste. During irradiation, the waste is placed in a chamber and exposed to microwave radiation. The radiation causes water molecules in the waste to vibrate rapidly, generating heat and increasing the temperature. Subsequently, the heat generated by the microwave radiation is sufficient to kill microorganisms and sterilize the waste. This technique can sterilize waste in a shorter time than other methods, such as autoclaving or chemical treatment. It also requires less energy than other waste treatment options, such as incineration or autoclaving, and it does not produce harmful emissions or by-products, making it a safer option for workers than incineration. Nonetheless, microwave irradiation equipment can be expensive to purchase and maintain, making it less accessible to smaller healthcare facilities or clinics.[32]

Table 2: **Comparative Analysis of Major Waste Treatment Technologies**

Technology	**Waste Streams Treated**	**Key Advantages**	**Key Disadvantages**	**Relative Cost**
Incineration	Municipal solid Biomedical and hazardous waste	Destroys pathogens & toxics Cuts volume up to 90% Steam/electricity generation	Emits GHGs, particulates, and dioxins unless well-controlled High capital and pollution-control costs	High
Mechanical-Biological Treatment (MBT) **(non-incineration)**	Mixed municipal waste pre-segregated	Lower emissions than thermal methods Recovers recyclables & biogas	Longer processing time Residual rejects still need disposal/ incineration	Medium

[31] Ghasemi, M. K., & Yusuff, R. Bt. M. (2016). Advantages and disadvantages of healthcare waste treatment and disposal alternatives: Malaysian scenario. *Polish Journal of Environmental Studies*, *25*(1), 17–25.

[32] Diaz, L. F., Savage, G. M., & Eggerth, L. L. (2005). Alternatives for treating and disposing healthcare wastes in developing countries. *Waste Management*, *25*(6), 626–637.

Chemical Treatment	Hazardous liquids/slurries Metal-bearing wastes	Neutralizes toxins/ metals Adaptable to many chemistries	Generates secondary residues needing landfill Ongoing reagent costs & handling risks	Medium
Pyrolysis	Organic/ biomass Plastics & tyres	Produces sellable fuels & char Lower air emissions vs. Incineration	Feed must be dry & homogeneous Capital & operating know-how	Medium-High
Plasma Gasification	Heterogeneous MSW Hazardous and e-waste	Nearly destruction of toxins Minimal ash/landfill needs High-grade syngas for power	Very high power demand & capex Complex O&M, limited global track record	Very high
Autoclaving (Steam Sterilisation)	Infectious & lab medical waste	Proven pathogen kill No toxic air emissions Lower capex than Incineration	Consumes steam/ energy Equipment needs strict maintenance No volume reduction unless followed by shredding	Low-Medium
Microwave Irradiation	Medical & lab wastes with sufficient moisture	Rapid cycle time Lower energy than autoclave/incinerator No combustion emissions	High unit cost for small facilities Limited throughput; metal items must be removed	Medium

Biomedical waste management techniques differ significantly in terms of efficiency, cost, environmental impact, and applicability. High-temperature technologies such as incineration and plasma gasification provide effective volume reduction and energy recovery, but they are capital-intensive and emit pollutants, making them unsuitable for resource-constrained places. Alternatives such as autoclaving, microwave irradiation, and mechanical-biological treatment are cleaner and often less expensive, albeit they may necessitate pre-treatment or additional disposal procedures. Advanced procedures such as pyrolysis and chemical treatment offer promise for converting biomedical waste into reusable products, but their operational complexity limits scalability.[33] In developed nations, new technologies such as electron beam irradiation and supercritical water oxidation are being investigated to improve safety and sustainability.[34]

4. Comparative Lessons from BRICS Nations

Biomedical waste management (BMWM) strategies exhibit substantial diversity across BRICS nations, each reflecting distinct regulatory structures, technological adoption, enforcement mechanisms, and compliance frameworks (*see* Table 3).[35] In China, BMW is characterized by a highly centralized regulatory approach. The government enforces stringent penalties for non-compliance, facilitating high adherence among healthcare facilities.[36] Significant investments in advanced waste-to-energy technologies, notably plasma gasification and autoclaving, have substantially decreased untreated waste volumes. Real-time waste tracking systems provide transparency and enhance operational oversight. Transferable elements for India from China's experience include establishing centralized digital monitoring systems, rigorous penalty structures, and strategic investment in advanced technological infrastructure. Brazil contrasts with China's centralized control by adopting a decentralized, market-oriented approach heavily reliant on public-private partnerships (PPPs).[37] The decentralization of waste treatment services, driven by fiscal incentives and explicit green governance mandates, has significantly boosted innovation and compliance.[38] The active role of subnational governments, combined with the integration of extended producer responsibility (EPR) mechanisms into healthcare financing frameworks, presents a highly successful policy innovation.[39]

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33 Tawo, O. E., & Mbamalu, M. I. (2025). Advancing waste valorization techniques for sustainable industrial operations and improved environmental safety. *International Journal of Scientific and Technology Research*, *14*(2), 127–149.

34 Pavlov, Y. S., Petrenko, V. V., Alekseev, P. A., Bystrov, P. A., & Souvorova, O. V. (2022). Trends and opportunities for the development of electron-beam energy-intensive technologies. *Radiation Physics and Chemistry*, *198*, 110199.

35 Zorina, A., & Yapryntsev, I. (2024). Images of corporeality in law: The experience of the BRICS countries. *BRICS Law Journal*, *11*(1), 58–83.

36 Mao, K., Zhu, Y., Zhao, Zh., & Shan, Y. (2020). Authoritarian environmentalism and environmental regulation enforcement: A case study of medical waste crime in northwestern China. In N. South & A. Brisman (Eds.), *Routledge international handbook of green criminology* (2nd ed., pp. 382–400). Routledge.

37 Mu, R. (2008). *Public-private partnerships for expressways in China: An agency theory approach* (paper presented at IEEE/NGI conference on infrastructures (Rotterdam)). https://repository.tudelft.nl/record/uuid:f5431f5b-54c7-4943-aecc-4348ef27f7bf

38 Gao, Y., Li, Zh., & Wang, Zh. (2025). Fiscal decentralization, green innovation and low-carbon transition of heavily polluting firms. *Journal of Environmental Management*, *380*, 124897.

39 Cai, Y., & Choi, T. M. (2019). Extended producer responsibility: A systematic review and innovative proposals for improving sustainability. *IEEE Transactions on Engineering Management*, *68*(1), 272–288.

India can leverage Brazil's PPP and EPR frameworks to enhance localized and economically sustainable BMWM solutions.

Russia employs a mixed governance model, wherein regional authorities predominantly manage general waste streams albeit without adequate specialized regulations explicitly tailored to biomedical waste.[40] Despite these regulatory gaps, Russia's strengths lie in its initiatives focused on environmental education, stakeholder engagement, and public-sector transparency, thereby indirectly promoting compliance.[41] India could benefit from adopting Russia's soft regulatory mechanisms strategies, focusing particularly on education, public awareness campaigns, and transparent information dissemination. Meanwhile, South Africa integrates national BMWM guidelines with substantial municipal autonomy, enabling flexible, context-specific implementation at the local level.[42] The decentralized regulatory structure facilitates grassroots community engagement, allowing localized monitoring mechanisms that significantly improving accountability and compliance. South Africa's approach underscores the efficacy of linking public health services directly with waste management operations, which could substantially enhance India's community-level BMWM accountability and effectiveness.[43] Drawing from these diverse experiences, India's BMWM strategy could adopt a hybrid regulatory framework integrating China's robust centralized monitoring infrastructure, Brazil's PPP-driven decentralized service delivery and EPR mechanisms, Russia's educational outreach and transparency initiatives, and South Africa's effective municipal-level accountability practices.

Table 3: **BMWM Frameworks Across BRICS Nations**

Country	**Regulatory Approach**	**Technological Advancement**	**Compliance Rate**	**Enforcement Mechanisms**
China	Centralized and strictly punitive	Plasma gasification, autoclaving	High	Real-time tracking, stringent penalties

40 Proskuryakova, L. (2021). Policy and governance for waste management in Russia. In P. Singh et al. (Eds.), *Waste Management Policies and Practices in BRICS Nations* (pp. 217–230). CRC Press.

41 Vinogradova, T. (2022). Improving green budget decisions and transparency through public participation: Evidence from Russia. *Public Sector Economics*, *46*(3), 385–401.

42 Van Wyk, M. W. (2011). *An evaluation of the implementation of the normative objectives set for Environmental Management Frameworks in selected case studies in Gauteng and the Northwest Province, South Africa* (Thesis). http://hdl.handle.net/11427/11258

43 Agenbag, M. H. A., Human, I. S., & Schutte, D. (2022). Local government environmental health services: Fundamentals for effective municipal service delivery and preventive health outcomes. *Journal of New Generation Science*, *20*(2), 40–54.

Brazil	Decentralized, PPP-driven, EPR	Waste-to-energy, recycling systems	High	Fiscal incentives, subnational governance
Russia	Mixed approach; Regional governance	Limited targeted technologies	Moderate	Environmental education, transparency
South Africa	Decentralized; Municipal autonomy	Autoclaving, localized technologies	Moderate to High	Community monitoring, public health integration
India	Mixed, decentralized SPCBs	Incineration, limited advanced tech	Moderate	Variable, limited centralized tracking

India's reliance on decentralization without real-time oversight, unlike China's centralized digital compliance architecture, hampers accountability. The success of PPPs in Brazil hinges on robust institutional checks something that India's fragmented pollution control boards lack.

4.1. Public-Private Compliance Incentive Model (PPCIM)

The Public-Private Compliance Incentive Model (PPCIM) represents a pragmatic and adaptive governance mechanism for enhancing biomedical waste (BMW) management, especially in rapidly developing economies like the BRICS bloc.[44] This model is grounded in the principle of collaborative accountability, wherein public regulatory institutions and private healthcare or waste treatment providers share responsibility for ensuring environmental and public health compliance. PPCIM operates through regulatory enforcement, fiscal incentives, and technological support to align private sector behavior with public health goals.[45] Drawing on Principal-Agent Theory, PPCIM aims to align incentives between the regulator (principal) and HCFs (agents) through real-time tracking and conditional subsidies. In Brazil and South Africa, public authorities have developed contractual frameworks and accreditation systems encouraging private healthcare providers to outsource waste treatment to certified third-party facilities.[46] Russia and China have leveraged state-owned enterprises and private contractors under centralized monitoring

44 Kvanina, V., Kovalenko, E., & Vypkhanova, G. (2023). Improving the legislation on public-private partnerships in environmental protection in the BRICS countries. *BRICS Law Journal*, *10*(3), 106–121.

45 World Health Organization. (2024). *Governance of the private healthcare sector in low- and middle-income countries: A scoping review of approaches, effectiveness and enablers*. https://iris.who.int/server/api/core/bitstreams/578d5072-113a-4e4a-b22b-6a093dd5740a/content

46 Joachim, M. (2020). *Constructing: Relationships, human resource management and culture of quality–The case of hospital do subúrbio, a Brazilian healthcare public-private partnership* (PhD dissertation). https://deepblue.lib.umich.edu/bitstream/handle/2027.42/163172/mjoachim_1.pdf;sequence=1

systems to ensure BMW's traceability and environmentally sound disposal. Under the BWMR, 2016, India has incorporated several PPCIM-like elements, such as mandating membership in CBWTFs for small and mid-sized healthcare facilities, and have further offered financial assistance or relaxed compliance timelines for entities that adopt eco-friendly treatment technologies. Moreover, state pollution control boards are empowered to issue compliance certificates, link emission monitoring data to regulatory dashboards, and impose penalties on public and private violators, creating a balanced incentive-penalty framework. By promoting a cooperative rather than adversarial relationship between regulators and healthcare actors, the PPCIM enables scalable and sustainable waste governance.[47] Importantly, its success hinges on the robust institutional capacity and clearly defined accountability structures, which vary across BRICS nations.[48] As a model, PPCIM offers significant potential for replication and refinement, especially in contexts where state resources are limited but public health risks from untreated biomedical waste are high.[49]

5. Sustainable Development Goals and BRICS Collaboration

India's challenges in biomedical waste management intersect directly with several critical targets under the United Nations Sustainable Development Goals (SDGs). Effective BMWM practices directly support SDG 3 (Good Health and Well-being) by significantly reducing the risk of infectious disease transmission through the safe handling, segregation, and disposal of hazardous biomedical waste.[50] This has tangible health outcomes, as demonstrated in Brazil, where PPP-driven advanced waste treatment systems substantially lowered hospital-acquired infections and enhanced healthcare worker safety. Effective BMWM also directly supports SDG 6 (Clean Water and Sanitation) by preventing harmful medical contaminants from entering water systems, thereby safeguarding water quality and public health, a notable outcome seen in China's centralized wastewater treatment initiatives linked to healthcare facilities. Additionally, BMWM contributes significantly to SDG 12 (Responsible Consumption and Production) by encouraging sustainable waste

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47 Izuchukwu Precious, O., Zino Izu, O., Chudi, F. A., & Ojevwe, A. T. (2025). Public-private collaborations in waste management: Evaluating policy effectiveness and governance models in Nigeria. *Journal of Integrity in Ecosystems and Environment*, *3*(2), 1–24.

48 Wei, D., & Rafael, A. P. (2023). Influencing companies' green governance through the system of legal liability for environmental infractions in China and Brazil: Lighting the way toward BRICS cooperation. *BRICS Law Journal*, *10*(2), 37–67.

49 Gupta, P. P., Bankar, N. J., Mishra, V. H., Sanghavi, S., & Badge, A. K. (2023). The efficient disposal of biomedical waste is critical to public health: Insights from the Central Pollution Control Board Guidelines in India. *Cureus*, *15*(10), e47303.

50 Shetty, V. P., Akshay, S. D., Thilai, B. D., & Deekshit, V. K. (2025). Biomedical waste management: Navigating the challenges to achieve the promise of sustainable development goal. *Waste Disposal & Sustainable Energy*, *7*(2), 303–321.

management practices such as recycling, reuse, and waste generation reduction at the source, successfully implemented in South Africa through municipal-level recycling and community engagement programs.[51]

To effectively integrate BMWM within their national SDG reporting frameworks, specific measures and indicators could include: the percentage of biomedical waste treated versus generated; the prevalence of healthcare-associated infections linked to waste management practices; the number of healthcare facilities complying fully with BMWM regulations; and reductions in water contamination incidents related to biomedical waste.[52] BRICS nations have shown measurable progress using such indicators; for instance, China has employed real-time tracking systems to achieve near-complete compliance and transparent reporting. Brazil's extended producer responsibility (EPR) systems include explicit accountability measures tied directly to SDG 12 outcomes.[53] India could leverage these insights by advocating for a BRICS Biomedical Waste Management Task Force. This task force would develop standardized BMWM indicators aligned with SDGs, monitor cross-border compliance, facilitate joint pilot projects, and encourage regional innovation. Such collaborative efforts would significantly enhance technical capabilities, strengthen regulatory frameworks, and amplify collective bargaining power in global climate-health governance, effectively aligning national and regional efforts toward achieving broader sustainability targets.

Table 4: **Indicators for Biomedical Waste Management Aligned with SDGs**

SDG Target	**Indicator**	**Description**	**BRICS Best Practices**
SDG 3.9 Reduce illnesses from hazardous chemicals and waste	Percentage of healthcare facilities with full BMWM compliance	Measures regulatory compliance with BMWM Rules	China – 85%+ via digital compliance enforcement

[51] Kumar, A. (2024, August). *Accelerating progress in SDG-6 (Clean water and sanitation) in South and South-West Asia subregion*. South and South-West Asia Office, Economic and Social Commission for Asia and the Pacific. https://repository.unescap.org/server/api/core/bitstreams/096e2072-a7e2-4686-8731-21d8e1254b00/content

[52] Deepak, A., Kumar, D., & Sharma, V. (2021). Developing an effectiveness index for biomedical waste management in Indian states using a composite indicators approach. *Environmental Science and Pollution Research International*, *28*(45), 64014–64029.

[53] Fox, T. M. (2018). *Co-opting sustainabilities: The transformative politics of labor and extended producer responsibility under Brazil's national solid waste policy* (PhD dissertation). https://dspace.mit.edu/bitstream/handle/1721.1/118208/1054488845-MIT.pdf?sequence=1&isAllowed=y

SDG 6.3 Improve water quality by reducing pollution	Percentage of healthcare waste pre-treated before discharge	Tracks on-site liquid waste treatment & pre-disposal sanitation	Brazil – Integrated wastewater-BMWM facilities
SDG 12.4 Environmentally sound waste management	Percentage of biomedical waste treated vs. generated	Proportion of total BMW that is properly treated	South Africa – 95%+ in metro municipalities
SDG 12.5 Substantially reduce waste generation	Percentage of recyclable/ reusable biomedical material recovered	Measures circular economy integration in BMW streams	Brazil – Active EPR & recycling under PPPs
SDG 17.18 Enhance data availability	Percentage of HCFs with real-time waste tracking system	Adoption of barcoding, OCEMS, and digital dashboards	China – Universal digital tracking since 2015

The table (*see* Table 4) lists five critical SDG targets and their accompanying metrics, which can be used as benchmarks for national performance and BRICS collaboration. Under SDG 3.9, which aims to minimise sickness caused by hazardous substances and waste, the proportion of healthcare facilities (HCFs) in full compliance with BMWM guidelines serves as a key indicator. China's integration of digital compliance systems has increased compliance rates above 85%, demonstrating the benefits of centralised enforcement. For SDG 6.3, the percentage of healthcare waste that is pre-treated before release reflects water pollution reduction, with Brazil setting the standard through integrated wastewater and BMWM infrastructure. Whereas, SDG 12.4 is centred on environmentally responsible waste management, and South Africa exemplifies best practices by processing over 95% of biomedical waste in metropolitan areas. SDG 12.5 aims to reduce waste generation, as assessed by the recovery rate of recyclable or reusable biomedical materials an area in which Brazil excels thanks to aggressive Extended Producer Responsibility (EPR) programs and public-private partnerships. Finally, SDG 17.18 relies on improving data availability; the proportion of HCFs that use real-time waste tracking systems, such as barcoding and Online Continuous Emission Monitoring Systems (OCEMS), is critical. China leads the way in this regard, having developed a universal tracking system in 2015. These indicators not only encourage accountability and harmonisation among the BRICS nations, but they also serve as a foundation for transnational cooperation, regulatory convergence, and long-term policy innovation.

Conclusion

As healthcare systems prioritise operational efficiency and revenue, the environmental impact of biomedical waste management (BMWM) risks being overlooked. True sustainability in healthcare necessitates a shift from cost containment to long-term environmental stewardship and systemic resilience. This article emphasises the importance of waste minimisation techniques and investments in sustainable technologies such as autoclaving, plasma gasification, and real-time tracking systems for healthcare facilities of all sizes. These techniques are not only ecologically friendly; they also provide important co-benefits such as improved infection control and increased community confidence. However, the analysis appreciates that structural disadvantages, such as poor infrastructure, regulatory enforcement gaps, and institutional capacity asymmetries, impede the route to meaningful transformation. Small and unauthorised establishments, which frequently operate on the edges of the regulatory net, bear disproportionate compliance burdens. Hence, addressing this inequality necessitates a targeted policy response. Accordingly, to that purpose, this article proposes a multifaceted strategy:

(i) Expanding the Public-Private Compliance Incentive Model (PPCIM) across states, using fiscal and effective tools such as green tax credits, emission-based subsidies, and differential compliance windows to encourage compliance.

(ii) Mandating the ubiquitous use of barcoded tracking systems and OCEMS to improve real-time regulatory visibility and deter noncompliance, particularly in high-risk metropolitan areas.

(iii) Creating a BRICS Biomedical Waste Management Task Force charged with developing harmonised cross-national procedures, exchanging technical blueprints, and pooling financing for mobile and rural waste treatment facilities through the New Development Bank (NDB).

(iv) Implementing performance-based grants for state pollution control boards, linked to measurable outcomes such as the percentage of HCFs in compliance and the reduction in untreated waste volumes.

(v) Integrating BMWM indicators into national SDG reporting frameworks to ensure that environmental measures are transparent and internationally benchmarked.

This article positions biomedical waste as a cornerstone of sustainable public health policy by presenting it as an opportunity for innovation, climate-health integration, and international cooperation, rather than a requirement for regulatory compliance. Comparative lessons from BRICS countries show that collaborative governance, when supported by technological adoption and budgetary alignment, can transform biomedical waste from a persistent threat to a catalyst for environmental justice and equitable development.

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