



# Quality-Improvement Approaches to Biomedical Waste Management in Tertiary Hospitals: Global Evidence, Challenges and Future Directions

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## ABSTRACT:

**Introduction:** Biomedical waste management (BMW) remains a critical challenge for health systems globally, particularly in low and middle-income countries (LMICs) where rapid patient turnover, high waste volumes, limited infrastructure and inconsistent compliance increase risks to healthcare workers (HCWs), patients and the environment. Tertiary-care hospitals generate complex waste streams and require robust monitoring, training and quality-improvement (QI) systems to ensure safe and sustainable practices. Despite well-established frameworks such as WHO guidelines and India's Biomedical Waste Management (BMW) Rules 2016 and amendments, significant gaps persist in segregation, transport, storage, occupational safety and treatment processes.

**Methods:** A narrative review was conducted using PubMed, Scopus, Web of Science and Google Scholar (2010-2025). Search terms included "biomedical waste", "healthcare waste", "segregation", "quality improvement", "PDSA", "training", and "occupational safety". Human studies, hospital-based investigations and QI interventions published in English were included. Data were synthesised thematically across regulatory frameworks, segregation practices, transport and storage systems, treatment technologies, KAP assessments, occupational hazards, digital monitoring tools and QI models.

**Results:** Across regions, segregation accuracy, PPE compliance, NSI rates and waste-generation indicators remain suboptimal, especially in LMIC tertiary hospitals. Studies consistently demonstrate poor KAP among newly recruited, contractual and housekeeping staff. Training interventions whether structured workshops, refresher modules or digital learning produce measurable improvements in segregation compliance, PPE adherence and risk perception. QI strategies, including Plan-Do-Study-Act (PDSA) cycles, Lean redesign of waste workflows, audit feedback loops and barcoding-based digital tracking, significantly strengthen waste-management performance. Persistent challenges include infrastructural gaps, inadequate storage, irregular transport routes, lack of supervision, behavioural barriers, and inconsistent enforcement at facility and state levels. Emerging innovations such as RFID tracking, AI-driven monitoring, and green treatment technologies offer promising future directions.

**Conclusions:** Studies demonstrates that improving BMW requires an integrated approach combining continuous training, QI-driven system redesign, regular monitoring and digital traceability. Tertiary-care hospitals given their complexity, high waste loads and diverse workforce must prioritise structured training, standardised audits, leadership engagement and technology-enabled tracking to enhance safety, compliance and environmental performance. Sustainable improvements are most



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likely when BMW is embedded within broader infection prevention and control (IPC) and hospital quality frameworks.

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## Introduction

Biomedical or health-care waste is broadly defined as any waste generated during the diagnosis, treatment or immunisation of humans or animals, or related research and production of biologicals, and includes items ranging from used needles and syringes to soiled dressings, laboratory cultures, anatomical waste and expired pharmaceuticals. World Health Organization (WHO 2014, updated 2024) guidance on health-care waste management and the Indian Bio-Medical Waste Management Rules 2016 adopt similar definitions while emphasising risk-based categorisation into non-hazardous “general” waste and hazardous fractions that are infectious, toxic, chemical, pharmaceutical or radioactive. WHO estimates that about 85.0% of health-care waste is non-hazardous, while the remaining 15.0% is hazardous and can pose significant risks if not handled appropriately (World Health Organization 2024; Janik-Karpinska et al 2023). These hazardous streams include infectious waste, sharps, pathological waste, chemical and cytotoxic waste and radioactive materials, which require specialised segregation, treatment and disposal as outlined in WHO’s “Safe Management of Wastes from Health-Care Activities” and the Central Pollution Control Board (CPCB) guidelines in India.

Janik-Karpinska et al (2023) reported that health-care waste accounts for approximately 1-2% of total municipal waste but is disproportionately important because of its infectious and toxic components; about 85.0% is non-hazardous, whereas 15.0% is hazardous, mirroring WHO estimates. Global data indicate wide variation in waste generation per bed, with hazardous health-care waste production in high-income countries reaching up to 11 kg per hospital bed per day compared with up to 6 kg/bed/day in low-income countries, although under-segregation in low-income settings probably leads to underestimation of the true hazardous fraction (World Health Organization 2023; UNDP 2024). Nematollahi et al (2025) in a recent multi-country review noted that overall health-care waste generation ranges from <1 kg to >8 kg/bed/day depending on hospital size, case-mix and level of care, with tertiary centres consistently reporting the highest values. Kenny et al

(2021) highlighted that rising global health expenditure, population ageing, chronic disease burden and pandemic-related infection-prevention measures (e.g. PPE) are collectively driving sustained growth in health-care waste volumes and associated environmental footprints.

In low- and middle-income countries (LMICs), the problem is compounded by infrastructural and governance gaps. Janik-Karpinska et al (2023) observed that many LMIC hospitals lack adequate segregation systems and rely heavily on low-tech options such as open dumping or low-temperature incineration, with incomplete combustion and uncontrolled emissions. Krishnamurthy et al (2024) reported that India generated approximately 656 tonnes of biomedical waste per day in 2020, with an additional 84.6 tonnes/day during the COVID-19 pandemic period, based on CPCB data, underscoring the surge in hazardous waste associated with large-scale use of disposables and PPE. Dixit et al (2022) assessed biomedical waste management across 56 health-care facilities in Uttar Pradesh and found that while tertiary centres had better availability of guidelines and colour-coded bins, overall segregation, hub cutter use, timely transport and staff awareness were suboptimal across all levels, particularly in primary and private facilities. Similar gaps have been reported from other Indian tertiary hospitals, where knowledge and practice scores were only moderate among nurses and housekeepers despite the presence of BMW Rules and on-paper contractual arrangements with common biomedical waste treatment facilities (Krishnamurthy et al 2024).

Tertiary care centres are uniquely important in this context because they generate the most complex mix of waste streams. Janik-Karpinska et al (2023) and Kenny et al (2021) note that large teaching hospitals concentrate high-dependency units (ICUs), operating theatres, interventional suites, oncology day-care, dialysis units and diagnostic laboratories, all of which produce high volumes of infectious, chemical and pharmaceutical waste requiring advanced management. Dixit et al (2022) demonstrated that medical colleges and district hospitals in India had many more observed “high-risk” sites (OTs, labour rooms, laboratories, emergency departments) than



lower-level facilities, and yet basic process lapses like absence of readable BMW charts, lack of lids on containers and inconsistent use of hub cutters were common even in these apex institutions. Krishnamurthy et al (2024) similarly showed that in a 900-bed tertiary hospital in Puducherry, only about half of staff nurses had high-category practice scores despite relatively good knowledge and attitude, indicating that system and organisational factors limit translation into consistent practice.

The risks of poorly managed biomedical waste extend to health-care workers (HCWs), patients, waste handlers and surrounding communities. World Health Organization (2024) estimates that unsafe injections and improper sharps disposal are responsible for tens of thousands of new HIV infections and hundreds of thousands of hepatitis B and C infections globally each year. Hosseinipalangi et al (2022), in a systematic review and meta-analysis of 113 studies including >525,000 HCWs, reported a pooled global incidence of needle-stick injuries (NSIs) of 43%, with the highest rates in the WHO African Region; NSIs most frequently occurred during waste disposal and were strongly associated with recapping and inadequate training. Sepandi et al (2023) found that 25.3% of HCWs in Iranian military hospitals reported at least one NSI in the preceding year, with night shifts, overtime, needle recapping and older age as significant predictors. In the Indian context, Dixit et al (2022) documented that 12% of doctors and nurses in Etawah district reported NSIs in the prior 12 months, and highlighted lack of regular training, budgetary constraints and logistic issues as major barriers to safe practice. Beyond occupational infections and injuries, the environmental consequences of open burning and low-temperature incineration include emission of dioxins, furans and particulate matter, as well as contamination of air, soil and groundwater, with downstream impacts on respiratory, cardiovascular and carcinogenic outcomes in the general population (Kenny et al 2021; Janik-Karpinska et al 2023).

Despite the existence of comprehensive regulatory frameworks such as India's Bio-Medical Waste Management Rules 2016 (with amendments in 2018, 2019 and 2023) and detailed CPCB guidelines, multiple studies from tertiary hospitals continue to report gaps in segregation, barcoding, PPE use and incident reporting. Krishnamurthy et al (2024) showed that training

attendance and better knowledge were strong predictors of satisfactory practice among staff nurses, yet a substantial proportion of nurses had never received formal BMW training. Mitiku et al (2022) in Ethiopia and other LMIC studies similarly report that even where rules exist, implementation is constrained by high patient loads, inadequate infrastructure, weak supervision and lack of continuous capacity-building. In parallel, reviews by Kenny et al (2021) and Janik-Karpinska et al (2023) underline that the environmental impacts of health-care waste remain poorly integrated into hospital quality and safety programmes, and that there is a paucity of robust, intervention-focused evaluations from LMIC tertiary settings.

Taken together, this literature indicates that biomedical waste management is a critical but under-addressed dimension of patient and worker safety, infection prevention and environmental sustainability, particularly in high-volume tertiary care hospitals in LMICs. While numerous cross-sectional Knowledge Attitude Practice (KAP) studies have documented suboptimal awareness and practice, far fewer have evaluated structured quality-improvement (QI) initiatives using Plan Do Study Act (PDSA) cycles, audit-feedback mechanisms or integrated training and monitoring models in real-world hospital settings. The present review therefore focuses on synthesising available evidence on hospital waste management with a specific emphasis on tertiary care facilities, HCW safety and QI-oriented interventions, in order to identify effective strategies, persisting gaps and research priorities relevant to resource-constrained health systems such as those in India.

## Methods

**Search Strategy:** This review was conducted as a narrative / scoping-style synthesis of the published literature on hospital biomedical waste management and related quality-improvement (QI) approaches. A structured search strategy was used to identify relevant studies published between 1 January 2010 and 31 December 2025. Four electronic databases were searched: PubMed/MEDLINE, Scopus, Web of Science and Google Scholar.

The search strategy combined Medical Subject Headings (MeSH) and free-text terms related to biomedical waste and hospital quality improvement. Core keywords and their variants included: "medical waste", "biomedical



waste management”, “hospital waste”, “healthcare waste”, “waste segregation”, “segregation compliance”, “healthcare workers”, “nurses”, “waste handlers”, “quality improvement”, “audit and feedback”, and “Plan Do Study Act” OR “PDSA”. These were combined using Boolean operators (e.g. “biomedical waste” AND hospital, “medical waste” AND “quality improvement”, “healthcare waste” AND “segregation” AND nurses). Only human studies conducted in hospital or health-facility settings and published in English were considered. The search targeted primary research articles (cross-sectional surveys, before–after interventional studies, quasi-experimental designs, qualitative and mixed-methods studies) and relevant implementation or QI reports focusing on biomedical or health-care waste management, hospital waste segregation, occupational hazards related to waste handling, staff knowledge–attitude–practice (KAP), or QI interventions in waste-management processes. Reviews, commentaries and policy briefs were used only for background and contextualisation and were not included in the primary synthesis.

**Study Selection:** All records retrieved from the database searches were exported into a reference-management software and duplicates were removed. Titles and abstracts were then screened in two stages. In the first stage, obviously irrelevant records were excluded based on title/abstract review. In the second stage, full texts of potentially relevant articles were obtained and assessed against predefined inclusion and exclusion criteria.

**Inclusion criteria were:**

1. Studies involving human participants (healthcare workers, waste handlers, patients or hospital populations).
2. Hospital-based or health-facility-based setting (tertiary, secondary, primary or mixed).
3. Explicit focus on biomedical / healthcare waste generation, segregation, collection, transport, treatment, storage, occupational exposure, or waste-related QI interventions.
4. Published in English between 2010 and 2025.

**Exclusion criteria were:**

1. Studies on **veterinary**, industrial, municipal or non-healthcare waste.
2. Non-empirical publications (editorials, letters without data, opinion pieces), conference

abstracts without full papers and theses not available as peer-reviewed articles.

3. Studies dealing exclusively with non-biomedical waste streams (e.g. general solid waste, food waste) without a biomedical or health-care waste component.

Where eligibility was unclear from the abstract, the full text was reviewed. When multiple publications reported overlapping data from the same study population, the most comprehensive or recent article was retained. Given the heterogeneity of study designs, settings and outcome measures, a narrative synthesis approach was adopted rather than meta-analysis. Included studies were grouped thematically into domains such as: global and national burden of hospital biomedical waste, segregation and compliance, occupational hazards and NSIs, KAP among healthcare workers, training and behaviour-change interventions, and quality-improvement or PDSA-based initiatives. Within each domain, findings were compared and contrasted to identify common patterns, gaps, context-specific challenges and implications for practice in tertiary-care settings, especially in low- and middle-income countries.

**Result: Global Overview of Hospital Waste Management:**

**WHO Guidelines and Global Policies:** The WHO defines health-care waste as all waste generated by health-care activities, including sharps, infectious materials, chemicals, pharmaceuticals and radioactive waste, and emphasises that around 15-25% of total health-care waste is hazardous, while the remaining fraction resembles domestic waste in composition (Chartier et al 2014; WHO 2024). WHO’s “Blue Book” on the safe management of wastes from health-care activities provides globally accepted technical guidance on segregation, colour-coding, packaging, labelling, internal transport, treatment and final disposal, and stresses the hierarchy of minimisation, segregation at source and safe treatment technologies as the core of an effective system (Chartier et al 2014). Subsequent WHO guidance and fact sheets highlight healthcare waste management as a core component of WASH, infection-prevention and emergency preparedness programmes, particularly in low- and middle-income countries (LMICs), where basic infrastructure and treatment capacity are often inadequate (WHO 2019; WHO 2024). Recently, global technical partners have also issued



operational guidance for health-care waste management in primary-care and low-resource settings, reinforcing WHO principles but adapting them to decentralised facilities and constrained budgets.

Building on WHO norms, many countries have developed national policies, emission standards and licensing frameworks for health-care waste, frequently integrating requirements for colour-coded segregation, secure storage, manifest systems for off-site transport and use of approved treatment technologies such as autoclaving or high-temperature incineration (Marcoux and Vogenberg 2015). In high-income settings, contemporary policy debates increasingly link health-care waste management with climate and circular-economy agendas, advocating waste minimisation, recycling of non-hazardous fractions and low-emission treatment options (Lee and Lee 2022; Aquino et al 2024).

**Global Waste-Generation Trends:** WHO estimates that high-income countries generate up to 0.5 kg of hazardous health-care waste per hospital bed per day, whereas low-income countries typically generate about 0.2 kg of hazardous waste per bed per day; however, poor segregation in many LMICs means a larger fraction of total waste is effectively hazardous in practice (WHO 2024). Minoglou et al (2017), in a cross-country analysis of data from 42 nations, reported that total health-care waste generation rates varied widely, from <1 kg to >10 kg/bed/day, and were strongly correlated with macro-indicators such as life expectancy, human development index and CO<sub>2</sub> emissions, underscoring how increasing service complexity and resource availability drive higher waste outputs. Mol et al (2022) synthesised continent-level data in a systematic review and noted that mean hospital waste generation ranged roughly from 0.5–3.0 kg/bed/day in Africa and Asia to higher levels in Europe and the Americas, with tertiary and university hospitals consistently producing the largest quantities because of intensive diagnostic and interventional workloads.

Janik-Karpinska et al (2023) highlighted that global health-care waste volumes have risen sharply over the last decade, accelerated by the COVID-19 pandemic, and documented hazardous medical waste generation rates up to 11 kg/bed/day in some high-income settings when PPE and single-use plastics were included. Cirstea et al (2025) similarly summarised that hospitals in the United States and Canada can generate 8.2-8.4 kg/bed/day of

total health-care waste, compared with 1.85-2.1 kg/bed/day in some Latin-American facilities and 0.5-0.6 kg/bed/day in hospitals from Nepal and Lao PDR, illustrating stark regional gradients within the Americas and Asia. In Africa, Meleko et al (2018) reported mean health-care waste generation of 1.9 kg/bed/day in Ethiopian health centres, with 37.0% classified as hazardous, and observed that higher patient load, laboratory services and delivery units were associated with greater waste production.

From a facility-type perspective, Kaposi et al (2024) analysed infectious health-care waste (IHCW) in Hungarian inpatient institutions and showed that university hospitals produced the highest infectious-waste loads (0.42 kg/bed/day), with generation strongly linked to healthcare-associated infections by multidrug-resistant organisms, number of ICU patients and educational activities. These findings echo earlier multi-country analyses indicating that tertiary-care centres with advanced diagnostic, surgical and critical-care services generate more complex and hazardous waste streams than secondary or primary facilities (Minoglou et al 2018; Mol et al 2022). Across regions, reviews consistently report that 75-85% of hospital waste is non-hazardous, but inappropriate mixing of general and infectious fractions in LMIC hospitals inflates the volume requiring specialised treatment and disposal (WHO 2015; Singh et al 2022; Janik-Karpinska et al 2023). These published studies indicate that while per-bed waste generation is highest in high-income countries, rapid expansion of hospital services and infection-prevention measures in LMICs is driving absolute increases in hazardous waste, often in systems where treatment capacity and regulatory oversight remain fragile (Minoglou et al 2017; WHO 2024).

**International Models of Effective Systems:** Several high-income countries have developed mature hospital-waste systems that are often cited as reference models. In the United States, regulated medical waste is primarily governed at the state level under a broad federal framework (Resource Conservation and Recovery Act, EPA) and infection-control guidance from the Centers for Disease Control and Prevention (CDC), which specify requirements for leak-proof packaging, puncture-resistant sharps containers and secure storage pending treatment (Marcoux and Vogenberg 2015; CDC 2024).



Marcoux et al (2015) emphasised that hazardous and pharmaceutical waste compliance has become a central component of hospital risk-management, linking waste regulations with occupational safety and environmental-protection mandates.

In the United Kingdom, the National Health Service (NHS) has implemented a highly standardised framework through Health Technical Memorandum (HTM) 07-01, which provides detailed guidance on classification, colour-coded segregation, packaging, labelling, transport and sustainable treatment of healthcare waste, and is reflected in local NHS trust waste-management policies (NHS England 2023; Sheffield HSC 2024). These policies explicitly integrate waste minimisation, carbon-reduction and circular-economy principles, and are supported by contractual frameworks that incentivise correct segregation and data-driven monitoring of hospital waste flows.

In East Asia, Japan and Singapore have pioneered more digitised approaches. In Singapore, the National Environment Agency (NEA) licenses waste-collection and treatment companies, enforces stringent requirements for biohazardous waste and, more recently, has rolled out an electronic manifest system to track biomedical waste from source to final disposal, improving traceability and compliance (NEA 2025; NEA 2025b). In Japan, national regulations for infectious and toxic industrial waste have mandated manifest systems and specialised treatment for hospital waste for over a decade and recent technology-roadmap documents highlight the adoption of advanced sorting, tracking and treatment options to improve safety and resource efficiency (NCCS 2016).

At a broader systems level, Lee and Lee (2022) analysed medical-waste management in Korean hospitals and identified medical-waste governance, operational management, staff training and environmental assessment as key factors contributing to sustainable “green healthcare” outcomes; they argued that structured training and clear operational protocols can significantly improve compliance within existing regulatory frameworks. Complementary global analyses underline that even in countries with robust policies, persistent challenges include under-segregation, variable compliance across facilities and the need for continuous training and auditing, especially in complex tertiary

centres (Janik-Karpinska et al 2023; Singh et al 2022; Alrabiah et al 2025).

**Table 1: Global hospital healthcare waste generation rates and key policy frameworks**

Region / Country	Typical HCW generation (kg/bed/day) *	Key policy / framework
United States / Canada	2-8.4 (total HCW)	State RMW regulations; EPA/RCRA; CDC infection-control guidance
Western Europe (UK)	2-4 (total HCW)	NHS HTM 07-01, trust-level waste policies
Eastern/Central Europe	0.4-3.0 (hazardous/IHCW)	National infectious-waste and manifest regulations
Latin America	1.8-2.1 (total HCW)	National hospital-waste rules; licensed treatment plants
Asia (mixed income)	0.5-5.7 (total HCW)	National BMW/HCW rules; e-manifest systems (e.g. Singapore)
Africa	0.5-2.0 (total HCW)	National HCW policies with variable enforcement

\*Ranges compiled from multi-country reviews and country-level studies; differences reflect inclusion/exclusion of general (non-hazardous) waste fractions and diverse hospital types



**Biomedical Waste Management in India:** Biomedical waste management (BMWM) in India is governed by a detailed regulatory framework that has evolved substantially over the last decade. The Bio-medical Waste Management Rules, 2016, notified by the Ministry of Environment, Forest and Climate Change (MoEFCC), replaced the earlier 1998 Rules and expanded coverage to all healthcare facilities, including clinics, laboratories and vaccination camps, while mandating segregation at source into four colour-coded categories, pretreatment of laboratory and microbiological waste, barcoding, and mandatory training of healthcare workers (HCWs). Capoor et al (2017) highlighted that the 2016 Rules also aligned Indian practice with WHO recommendations by specifying standards for autoclaving, incineration, emissions and deep burial, and by requiring maintenance of detailed records and annual reporting to State Pollution Control Boards (SPCBs).

At the systems level, the INCLIN Program Evaluation Network (IPEN) study group (2014) conducted a large situational analysis across 25 districts in 20 Indian states and found that a majority of primary and secondary facilities fell into “red” or “yellow” performance categories, with critical gaps in segregation, use of personal protective equipment (PPE), availability of guidelines and contractual linkages with CBWTFs. Central Pollution Control Board (CPCB) annual reports indicate that India generated roughly 600-800 tonnes/day of biomedical waste between 2016 and 2021, with a marked surge during the COVID-19 pandemic, and that while overall treatment capacity has improved, 5-10% of waste still remains untreated or inadequately treated in several states, largely due to poor segregation and infrastructure constraints. These national data underscore the implementation gap between legislative intent and ground-level practice.

State-level evaluations reveal wide heterogeneity in compliance. Singh et al (2014) evaluated BMWM practices in a tertiary care public hospital in the Rohilkhand region of Uttar Pradesh and reported suboptimal segregation, irregular use of PPE and inadequate documentation, despite the presence of written guidelines. Gadicherla et al (2016) assessed health facilities in Karnataka and found that many primary and secondary units lacked functional needle-cutters, labelled containers, or dedicated storage areas, leading to frequent mixing of infectious and general

waste. Singh et al (2013) documented practices at King George’s Medical University (KGMU), Lucknow, showing relatively better compliance in operation theatres and intensive care units but gaps in peripheral wards and outpatient areas, particularly in consistent use of colour-coded bins and record-keeping for waste sent to the CBWTF. More recent narrative appraisals from Uttar Pradesh suggest that while tertiary centres have improved infrastructure and authorization status, smaller facilities and rural hospitals continue to struggle with authorization, tracking and adherence to BMW Rules.

Facility-level compliance studies from tertiary hospitals across India further illustrate these challenges. Bhagawati et al (2015) in a tertiary care hospital in Delhi reported that although 89% of HCWs were aware of colour coding, only about two-thirds demonstrated correct segregation practices, and training was significantly associated with better scores. Malini et al (2015) in Puducherry found that doctors and nurses had better knowledge than housekeeping staff, but even among professionals, detailed understanding of categories and treatment methods was incomplete. Anand et al (2016) in a teaching institution in Haryana and Dudi et al (2016) in a tertiary facility reported similar patterns: moderate overall KAP levels, with pronounced deficits among paramedical and housekeeping personnel and a positive impact of prior BMW training. Imchen et al (2017) at a tertiary hospital in Lucknow noted that only about half of HCWs had adequate knowledge; while most reported “always” segregating waste, direct observation revealed inconsistent adherence at the point of generation.

More contemporary studies reflect both progress and emerging pressures. Krishnamoorthy et al (2022) documented biomedical waste disposal practices among HCWs in secondary and tertiary facilities in Tamil Nadu during the COVID-19 pandemic, reporting generally high adherence to PPE use and infectious waste segregation but persistent problems with overfilled sharps containers and inadequate training for contractual staff. Krishnamurthy et al (2024) identified predictors of satisfactory BMWM practices among staff nurses in a South Indian tertiary teaching hospital, showing that formal BMWM training, higher knowledge scores and female gender were independently associated with good practice, and recommending institutionalized, periodic



training and supportive supervision to sustain compliance. Sachan et al (2024) in a tertiary facility in Uttar Pradesh further demonstrated that structured training led to significant improvements in awareness scores among nursing staff, reinforcing the centrality of continuous capacity-building.

**Table 2: Selected Indian tertiary-care studies on biomedical waste management**

Study (year)	Setting & cadre	Sample size	Key findings & gaps (validated)
Malini & Eshwar, 2015	Tertiary-care hospital, Puducherry; doctors, nurses, other HCWs	337	Overall knowledge and attitude better in doctors than nurses/housekeeping; important gaps in practical implementation of segregation and use of PPE; prior training associated with better KAP.
Anand et al., 2016	Teaching/tertiary institution, Haryana; mixed HCWs	305	Moderate knowledge regarding BMW categories and colour coding; deficits more marked in nursing and support staff; practice scores lag behind knowledge; recommends regular

			training and supervision.
Dudi et al., 2016	Tertiary-level facility; paramedical staff	147	Paramedical staff showed partial awareness of BMW Rules; incorrect segregation and poor sharps handling common; limited exposure to formal BMW training; highlights need for focused education for non-medical cadres.
Imchen et al., 2017	Tertiary hospital, Manipur (Northeast India); doctors, nurses, lab technicians	314	78% had received BMW training. Segregation of general waste (95.2%) and human anatomical waste (80%) largely correct, but only 9.6% followed correct liquid-waste disposal. Training independently predicted satisfactory practice; lab technicians had the



			poorest practice scores.
Krishnamoorthy et al., 2022	Secondary and tertiary facilities, Tamil Nadu (COVID-19)	2,593 disposal observations	73% of disposal events were appropriate; one-quarter inappropriate. Non-compliance more frequent in certain cadres/units. Authors recommend targeted training, adequate supplies and continuous monitoring to approach 100% compliance.
Krishnamurthy et al., 2024	Tertiary teaching hospital, South India; staff nurses only	150	Overall BMW practice among nurses was moderate to good; prior training, longer work experience and higher knowledge scores predicted better practice. Recommends periodic, cadre-specific training and supportive supervision.

### Biomedical Waste Categories and Characteristics

**Classification of Biomedical Waste:** The World Health Organization (WHO) classifies health-care waste into non-hazardous (general) and hazardous fractions, with the latter comprising infectious, pathological, sharps, pharmaceutical, chemical, cytotoxic and radioactive wastes, as well as pressurised containers and heavy-metal-containing items such as broken thermometers and batteries (Prüss-Ustün et al 2014; WHO 2024). WHO estimates that 75-90% of waste generated in health-care facilities is non-hazardous general waste similar to domestic refuse, while 10-25% is hazardous and requires specific treatment and disposal (Kaposi et al 2024). Kaposi et al (2024) reported that hazardous health-care waste (HHCW) typically includes around 10% infectious waste and up to 5% chemical and radioactive waste by weight, though higher proportions have been reported in some settings due to poor segregation.

In India, the BMW Rules 2016 and subsequent amendments simplify these categories into colour-coded groups (yellow, red, white, blue) encompassing anatomical, soiled and infectious materials; contaminated plastics; sharps; and glass/metals, respectively, while general non-infectious waste is excluded from the BMW stream and should follow municipal solid-waste pathways (MoEFCC 2016; CPCB 2018). Bhalla et al (2019) highlighted that despite this streamlined four-category system, misclassification and mixing of general and infectious waste remain common in Indian hospitals, increasing both treatment costs and occupational risk.

At facility level, several empirical studies have characterised waste fractions in detail. Kaposi et al (2024) quantified waste streams in a large European university hospital and found that general waste constituted around 60-65% of the total, infectious waste 25-30%, and chemical/pharmaceutical waste 5-10%, with considerable variation between departments. Mazloomi et al (2019) examined clinical laboratory waste in Iran and reported that infectious and chemical/pharmaceutical fractions together accounted for more than half of the laboratory waste by weight, underlining the need for specialised handling and treatment in diagnostic units. Ghafuri and Nabizadeh (2017) focused specifically on cytotoxic waste from oncology wards and showed that, although relatively



small in mass, these residues contain highly persistent and genotoxic compounds that require stringent segregation and disposal pathways.

### Waste Generation in Different Hospital Units

Waste generation and composition differ substantially across hospital units because of variation in case-mix, intensity of care and use of disposable technologies. Anstey et al (2023) conducted a multicentre point-prevalence study across 51 adult intensive care units (ICUs) in Australia and New Zealand and demonstrated high utilisation of single-use consumables, with a median of 10 gowns, 10 syringes and 30 pairs of gloves discarded per occupied bed space per 12-hour shift, and low recycling rates for paper, glass and plastics. See et al (2023) synthesised ICU-focused audits and estimated that critical-care units may generate 7.1 kg of solid waste per bed per day, approximately 1.3 times that of non-ICU hospital wards, with a disproportionately large climate footprint. Corbin et al (2022) performed a 24-hour waste audit in a neuro-ICU during the COVID-19 pandemic and found that the majority of waste by weight was potentially recyclable general waste, but was frequently disposed of as infectious waste because of precautionary practices and extensive use of personal protective equipment (PPE).

Operating theatres (OTs) are recognised as major generators of high-value plastic and packaging waste. Pillay et al (2024) noted that OTs can contribute up to 20–30% of total hospital waste, driven by single-use drapes, gowns, instrument wraps and anaesthesia circuits. Almukhtar et al (2024) systematically reviewed sustainability interventions in operating rooms and reported that a large proportion of OT waste originates from non-contaminated packaging, which could be diverted from costly infectious-waste streams through better segregation and recycling programmes. Siraj et al (2025) analysed medical plastic waste in a teaching hospital and identified 19 common plastic items, many from surgical and procedural areas, and showed that a substantial fraction was technically recyclable if separated early and uncontaminated.

Dialysis units represent another high-intensity waste hotspot. Sahay et al (2023) conducted a prospective observational study in an Indian tertiary-care nephrology department and quantified daily dialysis waste using a spring balance, showing that plastic disposables

accounted for a major share of waste per haemodialysis session, alongside considerable water and chemical consumption. Cherain et al (2025) further demonstrated increasing trends of biowaste in haemodialysis services under a hub-and-spoke model, linking higher dialysis volumes to rising BMW treatment demands.

Obstetric and labour-room services also produce substantial infectious waste, particularly soiled linen, placental tissue and sharps. Rani and Rampal (2019) audited BMW generation in a 750-bed tertiary hospital in Jammu and reported an average of 116.37 g of infectious biomedical waste per bed per day overall, with the highest generation in gynaecology and obstetrics wards (315.61 g/bed/day); they also documented mixing of waste in labour rooms and wards and lack of safe processing tools in some areas. Khudhair (2018) analysed waste streams in an Iraqi teaching hospital and identified obstetrics as the largest producer of both general and hazardous waste, emphasising that high-throughput maternal-child units require special focus in BMW planning.

Clinical laboratories contribute a distinct mix of infectious and chemical waste. Mazloomi et al (2019) evaluated healthcare waste from eight clinical laboratories in Ilam, Iran, and found that approximately 56% of the waste comprised infectious and chemical–pharmaceutical fractions, with only 37% considered general waste, underscoring the need for tailored protocols for specimen containers, reagents and sharps in laboratory settings.

### Special Waste Challenges: OT Plastics, COVID-Waste and Cytotoxic Drugs:

Recent literature has highlighted the escalating challenge of plastic waste from operating theatres and other procedure-intensive units. Cho et al (2024) examined medical plastic packaging in hospital supply chains and showed that device packaging and single-use components contributed substantially to overall plastic waste volumes, many of which could be redesigned or made recyclable without compromising sterility. Siraj et al (2025) similarly demonstrated high volumes of plastic items such as syringes, infusion sets and sample containers, and classified them into contamination-based categories, identifying a large proportion as suitable for recycling if effective segregation at source is implemented.



The COVID-19 pandemic dramatically amplified PPE-related waste streams. Kaposi et al (2024) analysed healthcare-waste trends across several years in a university hospital and reported that the generation rate of hazardous healthcare waste increased to approximately 3.4 kg/bed/day during the pandemic, largely attributable to expanded use of disposable gowns, masks and gloves. Corbin et al (2022) in their neuro-ICU waste audit during COVID-19 found that infection-control precautions led to significantly higher consumption of PPE per patient and increased classification of waste as infectious, even when contamination risk was low, thereby inflating BMW treatment volumes. WHO has similarly warned that surges in PPE usage during COVID-19 generated large quantities of plastic and infectious waste that exceeded treatment capacities in many low- and middle-income countries.

Cytotoxic and pharmaceutical wastes pose specialised environmental and occupational hazards. Ghafuri and Nabizadeh (2017) quantified cytotoxic waste from oncology wards and showed that although the mass fraction was modest compared with other waste streams, residues of platinum-based and other chemotherapy drugs were detectable in effluents and solid waste, with potential ecotoxicity if not adequately contained. Khaksar et al (2022) emphasised that conventional wastewater treatment systems have limited capacity to remove cytotoxic drug residues and advocated advanced treatment processes and robust cytotoxic-waste segregation at ward level.

**Table 3: Biomedical Waste Categories, Sources, and Unit-Specific Characteristics**

Waste Category	Definition / Examples	Typical Hospital Sources	Evidence-Supported Characteristics (Based on Published Studies)	Key References
<b>General (Non-hazardous) Waste</b>	Paper, food waste, packaging, unconta	All non-clinical and clinic	WHO reports 75–90% of total HCW waste can be non-hazardous <i>if</i>	WHO 2024; Corbin 2022

	minated plastics	al areas	<i>segregation is appropriate.</i> During COVID-19, many facilities misclassified general waste as infectious due to PPE-heavy workflows (reported in several audits).	
<b>Infectious Waste</b>	Blood-contaminated items, dressings, catheters, PPE	ICUs, wards, labour rooms, emergency	ICU waste generation is consistently higher than general wards (higher PPE use, more disposables). Specific ICU audits report increased infectious waste during COVID-19. Labour rooms also show high infectious waste due to soiled linen and bodily fluids.	See 2023; Rani 2019
<b>Sharps Waste</b>	Needles, scalpels, lancets, broken glass	Wards, labs, ICUs, OTs	Several Indian tertiary-care audits show frequent overfilling of sharps	Bhalla 2019



			containers and inconsistent use of needle-cutters, increasing NSI risk. Poor segregation of sharps with general waste is widely documented.	
<b>Pharmaceutical Waste</b>	Expired or discarded medicines, vials, antibiotics	Pharmacy, ward, ICU	Lab-based waste auditing found 20-25% of clinical-laboratory waste consisted of pharmaceutical/chemical fractions in some facilities.	Mazloomi 2019
<b>Cytotoxic Waste</b>	Chemotherapy residues, contaminated gloves/IV sets	Oncology ward, day-care chemotherapy	Small in mass but highly hazardous. Published surveys show detectable chemotherapy-drug residues in hospital effluents, requiring strict segregation & advanced treatment.	Ghafuri 2017; Khakhsar 2022

<b>Chemical Waste</b>	Reagents, solvents, disinfectants	Labs, dialysis units, CSSD	Clinical labs generate relatively high proportions of chemical + infectious waste (~56% combined in Iranian tertiary-hospital laboratory audits). Dialysis units consume high volumes of disinfectants and dialysates.	Mazloomi 2019; Sahay 2023
<b>Plastic Medical Waste</b>	Syringes, tubings, IV sets, catheters, OT drapes/wraps	OTs, ICUs, dialysis units	Operating rooms contribute large volumes of non-contaminated and contaminated plastic waste. Multiple studies emphasize the potential for recycling of clean OT plastics if segregated at source. Dialysis units produce substantial	Pillay 2024;



			plastic waste per session.	
<b>Pathological Waste</b>	Human tissues, organs, placentas	OTs, labour rooms	Obstetrics and labour rooms generate high levels of anatomical waste including placental and blood-contaminated materials.	Rani 2019
<b>COVID-19 Related Waste</b>	PPE, masks, gowns, test kits	All units, especially ICUs	COVID-19 led to surges in hazardous waste, driven by massive PPE use. Waste audits reported substantial increases in infectious waste and increased misclassification.	Kaposi 2024; Corbin 2022

### Regulatory Framework (India and Global) Bio-medical Waste Management Rules 2016 and Amendments (2018, 2019, 2023)

In India, the Bio-medical Waste Management (BMW) Rules, 2016, notified under the Environment (Protection) Act 1986, replaced the earlier 1998 rules and marked a major shift towards a risk-based, systems-oriented regulatory framework. The 2016 Rules reduced the number of categories from ten to four (yellow, red, white (translucent) and blue), emphasised segregation at the point of generation, and made it mandatory for all healthcare facilities (HCFs) bedded and non-bedded to obtain authorisation and ensure treatment through authorised Common Bio-medical Waste Treatment Facilities (CBWTFs) or compliant in-house systems. The

Rules prescribe a maximum onsite storage time of 48 hours, mandate pre-treatment (disinfection/sterilisation) of laboratory and microbiology waste, and require phased elimination of chlorinated plastic bags and gloves to reduce dioxin and furan emissions from incineration. The 2018 Amendment strengthened several provisions, including compulsory barcoding and GPS-enabled tracking of BMW from source to final disposal, more stringent reporting formats, and explicit timelines for phasing out chlorinated plastic items. The 2019 Amendment further clarified definitions (e.g. “occupier”, “bedded facility”), extended barcoding deadlines, refined emission standards and tightened reporting obligations of State Pollution Control Boards (SPCBs). A recent synthesis by Sharma and Yadav (2021) highlighted that the BMW Rules 2016 and amendments align closely with WHO recommendations on segregation, colour-coding, treatment standards and occupational safety, but that effective implementation remains highly variable across Indian states.

The Central Pollution Control Board (CPCB) issues detailed technical guidelines on handling, treatment and disposal, including incinerator stack emission norms (dioxins/furans, particulate matter), autoclave validation, deep-burial restrictions and liquid-waste management from HCFs. CPCB also compiles annual BMW reports based on data submitted by SPCBs, summarising the number of authorised HCFs and CBWTFs, quantities generated and treated, and state-wise compliance patterns.

**Implementation Gaps Across Indian States:** Despite a robust legal framework, several empirical studies between 2010 and 2025 show substantial gaps in implementation at facility and state levels. Diwan et al (2023) assessed KAP and practices among 105 healthcare workers in a tertiary hospital in Chhattisgarh and found that although clinicians had relatively better knowledge and practices, paramedical and housekeeping staff showed important deficiencies in segregation, storage and PPE use, underscoring the need for continuous orientation and supervision. Dixit et al (2021) conducted an observational multicentric study of health facilities in Uttar Pradesh and documented variable compliance with BMW Rules 2016, with notable gaps in proper segregation, barcoding, timely handover to CBWTFs and record-keeping, particularly in primary and secondary-level facilities. These findings indicate



that, within Uttar Pradesh, tertiary centres may be relatively better prepared than peripheral units, but systemic shortfalls in training and monitoring remain. In Delhi, Pandey et al (2016) evaluated BMWM in a large tertiary-care teaching hospital and showed that despite the presence of a CBWTF contract and written SOPs, common deviations included overfilling of bins, incorrect disposal of general waste in BMW containers and inconsistent labelling of bags, highlighting a gap between policy and day-to-day practice. Subsequent audits from northern Indian tertiary centres have consistently confirmed that nursing staff and residents usually demonstrate better compliance than housekeeping staff, and that high workload and inadequate supervision are key barriers. Kerala is often cited as a relatively better-performing state because of the IMAGE CBWTF model, which provides centralised collection and treatment for >10,000 HCFs, GPS-tracked transport and regular training programmes (George B et al. 2024). World Bank's environmental system assessment for the Kerala Health Systems Improvement Program also noted that the state relies on a single centralised CBWTF and identified gaps in liquid-waste treatment and infection-control capacity at facility level, despite a generally progressive policy environment.

In Maharashtra, Gadircherla et al (2016) evaluated BMWM practices in selected HCFs and found that only around two-thirds complied with segregation norms and that routine training and structured supervision were often lacking, leading to mixing of infectious and general waste and over-reliance on CBWTFs without adequate in-house quality checks. Regulatory reports from Maharashtra Pollution Control Board and media investigations around CBWTF operations have also highlighted episodic non-compliance with emission norms and capacity constraints, particularly during the COVID-19 pandemic. Comparative analyses thus suggest that, even in relatively better-performing states like Kerala and Maharashtra, implementation is uneven, while states such as Uttar Pradesh and parts of north India continue to struggle with coverage of non-bedded facilities, staff training and robust monitoring systems.

## **Enforcement Challenges: CBWTF Capacity, Barcoding, Staffing and Monitoring**

Multiple recent reviews converge on the conclusion that the principal challenge in India is not the absence of legislation but weak enforcement and monitoring. Operational issues at CBWTFs include overloading, downtime due to poor maintenance, delays in collection from remote facilities and episodic non-compliance with stack emission norms or ash-disposal standards. Analyses from Kerala and other states have emphasised that reliance on a single CBWTF can create systemic vulnerability when logistical or regulatory disruptions occur (e.g. GST registration or consent-to-operate issues), leading to accumulation or unsafe storage of BMW at facility level. At the same time, environmental audits from Karnataka and other states have documented significant under-reporting, with up to 80-90% of HCFs failing to submit annual BMW reports in some years, making it difficult for SPCBs to maintain an accurate inventory or verify that all BMW is reaching authorised facilities.

Enforcement of barcoding and GPS-based tracking, mandated in the 2016 Rules and subsequent amendments, has progressed unevenly. While a subset of urban tertiary hospitals and CBWTFs have rolled out barcoding systems, several studies and regulatory reviews note partial or absent implementation in smaller facilities, with barcodes either not used or not linked to functional online monitoring platforms. Human-resource constraints further complicate enforcement: SPCBs are often under-staffed relative to the number of HCFs and CBWTFs they must inspect, and in many hospitals, infection-control and BMW committees exist on paper but meet irregularly, limiting the impact of internal supervision. Diwan et al (2023) and other facility-level KAP studies consistently highlight that housekeeping staff and waste handlers, who are at greatest exposure risk, are the least likely to receive structured, periodic training or vaccination against hepatitis B, reflecting a systemic neglect of front-line waste workers in enforcement and capacity-building efforts.



**Table 4: Key Features of India's BMW Rules 2016 Compared with Selected Global Standards**

Domain / Standard Aspect	India BMW Rules 2016 & Amendments	WHO "Safe Management of Wastes from Health-care Activities" (2014)	UK NHS / HTM 07-01 Framework
<b>Segregation &amp; Categories</b>	Four colour-coded categories (yellow, red, white, blue); mandatory segregation at source; 48-hour maximum onsite storage.	Recommends colour-coded segregation at point of generation; categories for infectious, sharps, chemical, pharmaceutical, radioactive and general waste; storage "as short as possible".	Standardised colour-coding (e.g. orange, yellow, purple streams) with detailed "waste streams" and EWC codes; strong emphasis on source segregation and contractual controls.
<b>Coverage of Facilities</b>	Applies to all HCFs (bedded and non-bedded) and CBWTFs; mandatory authorisation and annual reporting via SPCBs.	Recommends universal application in all health-care settings, including small clinics and outreach services; leaves legal enforcement	Applies to all NHS and independent providers contracted to NHS; contractual obligations ensure compliance with

		t to national authorities.	national and EU waste law.
<b>Treatment &amp; Disposal</b>	Priority to CBWTFs; prescribes standards for incineration, autoclaving, microwaving, deep burial (restricted), chemical disinfection and effluent treatment; phasing out chlorinated plastics.	Favors non-burn technologies where feasible; detailed guidance on incineration, autoclave validation, and environmentally sound disposal; discourages uncontrolled burial/open burning.	Emphasis on high-temperature incineration for certain streams and alternative treatments for others; strict emission limits and duty-of-care documentation.
<b>Traceability &amp; Barcoding</b>	Mandates barcoding and GPS-enabled tracking for BMW from source to CBWTF; implementation still incomplete in many states.	Encourages documentation and manifest systems but does not prescribe barcoding; leaves technology choice to countries.	Robust "waste tracking" and electronic duty-of-care systems for hazardous waste; extensive documentation from generator to final disposal.
<b>Occupational Safety</b>	Requires provision of PPE, training and Hepatitis-B immunisation	Strong focus on worker safety, including PPE, vaccination	Incorporates COSHH and health-and-safety laws; detailed guidance



	on for at-risk workers; emphasises NSI prevention, spill management and post-exposure prophylaxis.	, safety-engineered devices and training; integrates BMW into infection-prevention programmes.	on PPE, training, risk assessment and contractor management.
<b>Reporting &amp; Oversight</b>	SPCBs submit annual BMW reports to CPCB; HCFs must report accidents and submit annual data; enforcement capacity and data completeness vary widely between states.	Recommends national reporting and surveillance, but mechanisms context-specific; stresses monitoring of treatment facilities.	Regular reporting through NHS contracts and regulators (Environment Agency); periodic audits, inspections and public reporting of performance.

### Waste Segregation Practices:

**Importance of Segregation at Source:** Segregation at the point of generation is internationally recognised as the most critical step in biomedical waste management because it prevents mixing of infectious and non-infectious waste, reduces treatment costs and lowers occupational exposure risk for healthcare workers (HCWs). WHO guidance consistently emphasises that improper segregation multiplies the volume of waste requiring specialized treatment and increases the likelihood of needle-stick injuries and environmental contamination. In tertiary-care settings, where patient flow and procedural intensity are high, empirical studies demonstrate that the availability of colour-coded bins

alone does not ensure correct segregation. Instead, segregation quality depends on HCW behaviour, supervisory oversight and organisational support.

### Segregation Compliance in Hospital Settings:

**Evidence from Validated Studies:** Evidence from Indian tertiary hospitals shows that segregation compliance remains inconsistent despite adequate knowledge and availability of bins. Joseph et al. (2015) reported that although most doctors and nurses demonstrated good awareness of colour-coding, observed segregation lapses were frequent, particularly among housekeeping staff and interns. Mor et al. (2017), in a multicentre managerial survey, identified segregation at source as the single most challenging aspect of BMW management, noting that it required constant supervision to ensure adherence. Diwan et al. (2023) observed that HCWs who had received prior BMW training were significantly more likely to segregate waste correctly, yet recurrent errors such as improper disposal of plastics and sharps into incorrect bins continued to occur.

**Factors Associated with Poor Segregation:** Across all validated studies, several recurring determinants of poor segregation emerge. Improper segregation is linked to insufficient facility-level training, particularly among housekeeping workers who handle most BMW streams. Joseph et al. (2015) and Diwan et al. (2023) both found significant cadre-wise differences, with housekeeping staff demonstrating the lowest compliance due to minimal training and limited understanding of BMW rules. High workload and rapid staff turnover especially among interns, contract workers and cleaning personnel were also cited as major barriers.

Infrastructure-related issues, such as the inconsistent availability or poor placement of colour-coded bins, were identified in African studies as important contributors to mis-segregation. Insufficient supervision and lack of feedback loops were repeatedly highlighted by Mor et al. (2017) as systemic weaknesses that permit ongoing errors in segregation practice. Overall, validated evidence demonstrates that poor segregation is multifactorial driven by a combination of behavioural, organisational and infrastructural limitations highlighting the need for structured training, supportive



supervision and continuous quality-improvement mechanisms.

## Waste Collection, Internal Transport and Storage Practices

WHO and national guidance emphasise that safe healthcare waste management requires timely collection, closed and labelled containers, designated transport routes and secure interim storage with restricted access. The WHO Blue Book recommends at least daily collection, leak-proof containers, clearly marked trolleys and storage times generally <48 hours in warm climates, while CPCB guidelines for implementation of the BMW Rules 2016 specify colour-coded bags, covered trolleys with biohazard symbols, and central storage with impermeable flooring, drainage to effluent treatment plants and “authorised personnel only” access. In practice, observational studies from low- and middle-income settings consistently highlight gaps in these steps. Krishnamoorthy et al (2022) reported that during the COVID-19 pandemic in secondary and tertiary facilities in Tamil Nadu, collection was often delayed and bags were overfilled or inadequately sealed, despite reasonably good overall disposal scores. Savio et al (2025) documented across four tertiary care teaching hospitals in South India that, although most units had colour-coded bins, non-compliance persisted in the form of overflowing containers, mixed waste in central storage and irregular internal collection schedules. Njue et al (2015) in Kenya found suboptimal adherence to national healthcare waste guidelines, with unlabelled trolleys, lack of dedicated routes and inadequate temporary storage areas contributing to unsafe handling. More recently, a Kenyan county-level cross-sectional study by Across these studies, common non-compliance patterns include collection at irregular intervals, bins filled beyond three-quarters capacity, use of generic or damaged trolleys without biohazard labels, accumulation of mixed waste in corridors or at nursing stations, and central storage areas that lack clear demarcation, adequate ventilation or security. Such deviations from recommended protocols increase the risk of spills, occupational exposure and downstream environmental contamination, underscoring the need to integrate routine transport and storage audits into hospital quality-improvement programmes.

## Waste Treatment Technologies

WHO guidance and national regulatory frameworks describe several acceptable technologies for healthcare waste treatment, including autoclaving, microwaving, hydroclaving, chemical disinfection and incineration, often followed by shredding to render waste non-recognisable. Janik-Karpinska et al (2023) summarise that non-burn technologies (steam-based systems, microwaves) are suitable for most infectious waste streams, whereas high-temperature incineration is generally reserved for pathological waste, pharmaceutical residues and some hazardous materials. In India, CPCB guidelines and the BMW Rules 2016–2019 amendments prescribe autoclaving, microwaving or chemical treatment for microbiological and sharps waste, with incineration or deep burial (under strict conditions) for anatomical waste and certain drug categories, and mandate emission limits for dioxins and furans for existing incinerators.

At the same time, a growing body of environmental health literature has raised concerns about incineration. Ajay et al (2024), in a systematic review of dioxin emissions from biomedical-waste incinerators, showed that medical incinerators can be important local sources of polychlorinated dibenzo-p-dioxins and furans, with measured concentrations in stack gases and surrounding media that, in some settings, imply non-negligible lifetime excess cancer risk if poorly controlled. Studies linking population exposure to incinerator emissions also suggest detectable levels of dioxins and PCBs in human tissues or breast milk, although diet remains the major exposure pathway; these findings have prompted calls for stricter monitoring and a shift towards cleaner technologies.

Indian narrative and evaluation studies note operational challenges at Common Biomedical Waste Treatment Facilities (CBWTFs), including uneven geographic distribution, capacity gaps, inadequate maintenance, downtime of autoclaves or incinerators, and variable compliance with emission norms. Dhole et al (2024) highlight that, despite policy advances, treatment capacity has not always kept pace with rising BMW generation, particularly during COVID-19 surges, leading at times to over-reliance on incineration and risks of sub-optimal combustion. Recent Indian reviews therefore advocate phased expansion of non-burn technologies, stricter performance monitoring of



CBWTFs, and integration of environmental indicators into BMW performance dashboards.

### **Occupational Hazards Among Healthcare Workers:**

Occupational exposure represents a major justification for robust BMW systems. Janik-Karpinska et al (2023) emphasise that mismanaged healthcare waste can cause needle-stick injuries (NSIs), cuts, splashes and longer-term toxic exposures among healthcare workers (HCWs), waste handlers, patients and the surrounding community. Global systematic reviews by Mengistu et al (2021) and Bouya et al (2020) report pooled career-time NSI prevalence of around 56% and 43-45% respectively, with particularly high rates in low- and middle-income settings and in South-East Asia. An updated review by Abdelmalik et al (2023) focusing on nurses confirms that NSIs remain common worldwide, with developing countries showing significantly higher prevalence than high-income regions.

Indian data mirror this global picture. Naidu et al (2023) reported an incidence of 10.4 NSIs per 100 occupied beds per year in a western-India tertiary hospital, noting that inexperience and poor awareness of preventive measures were key contributors. Raj et al (2024) found a 12-month NSI prevalence of 31% among HCWs at a tertiary centre in Kochi, with intravenous cannulae and injection procedures most frequently implicated, and highlighted gaps in timely reporting and post-exposure prophylaxis despite relatively high HBV vaccination coverage. Savio et al (2025) observed that in four South-Indian teaching hospitals, sharps injuries and splash exposures clustered in areas with poor segregation, overflowing sharps containers and inadequate PPE use, and that higher perceived risk did not always translate into consistent protective behaviour.

Waste handlers are an especially vulnerable group. Das et al (2024) documented frequent occupational health hazards including NSIs, cuts and musculoskeletal problems among hospital waste handlers in tertiary hospitals in Karachi, with low training coverage and inconsistent glove, mask and boot use as significant determinants. Similar concerns are echoed in African and Asian studies that link irregular collection schedules, bin overflow and manual handling of unsegregated waste with elevated injury risk. Across settings, PPE availability and proper use remain central but imperfectly implemented controls. Studies from Indian tertiary

centres and European COVID-19 cohorts show that appropriate PPE (including gloves, masks/respirators, gowns and eye protection) significantly reduces infection and exposure risk, yet shortages, discomfort, cost and low risk perception contribute to non-adherence.

### **Knowledge, Attitude and Practice (KAP) Studies:**

Multiple KAP studies conducted across low- and middle-income countries consistently demonstrate that healthcare workers (HCWs) often possess inadequate knowledge and suboptimal practices related to biomedical waste management (BMW). In India, Singh et al. (2014) reported significant gaps in KAP among HCWs in a North Indian tertiary-care hospital, particularly in categories related to sharps handling and colour coding. Savio et al. (2025) demonstrated that low KAP scores were associated with higher rates of mixed waste in segregation audits across four South Indian teaching hospitals.

### **Training Interventions and Behaviour-Change**

**Strategies:** Structured training remains one of the most effective interventions for improving BMW compliance. In India, Shivashankarappa et al. (2024) showed that repeated in-service training improved correct segregation practices among nursing and housekeeping staff by double-digit margins. Digital training has also become increasingly relevant. Behaviour-change models such as COM-B (Capability–Opportunity–Motivation–Behaviour) and nudge theory have also been incorporated into BMW training interventions. Krishnamoorthy et al. (2022) highlighted that combining training with visual cues (signage, coloured liners, workflow nudges) significantly enhanced compliance in high-demand clinical settings during the COVID-19 pandemic. In general, repeated reinforcement, quarterly refresher sessions and blended (digital + in-person) training models demonstrate the strongest sustained improvements, as consistently reported in multiple Asian and African studies.

### **Quality Improvement Approaches in Waste Management:**

Quality-improvement (QI) methodologies have increasingly been applied to hospital waste-management workflows. The PDSA cycle is the most frequently used model. Lean and Six Sigma tools have also been applied to reduce waste-handling inefficiencies. Wang et al. (2025) used Lean principles to



redesign collection routes in a Maharashtra teaching hospital, reducing delays and bin overflow incidents. Digitised tracking technologies have emerged as a major innovation. Audit–feedback mechanisms remain essential to sustaining improvements. Regular audit cycles, combined with immediate feedback and visible display of compliance rates, have shown measurable benefits in study of Savio et al., (2025). Sustainability models emphasise leadership engagement, repeated micro-training, real-time monitoring dashboards and integration with hospital accreditation systems such as NQAS and Kayakalp.

**Monitoring and Evaluation of Healthcare Waste Management (HWM) Systems:** Effective monitoring and evaluation are foundational to biomedical/healthcare waste management systems because they convert written guidance into measurable compliance. WHO technical guidance and training/rapid assessment materials recommend routine tracking of key performance indicators (KPIs) such as waste generation per bed-day, the proportion of hazardous versus general waste, segregation accuracy at source, completeness of labelling/documentation across the internal chain, availability and use of personal protective equipment (PPE), and occupational safety indicators (including sharps-injury/needlestick events where feasible) (World Health Organization 2014). Evidence from intervention research indicates that healthcare-waste programmes most consistently measure knowledge/attitude/practice outcomes, while fewer studies track harder process and outcome KPIs (e.g., waste-volume reduction, compliance scores, or cost outcomes) over repeated time points—limiting conclusions about sustainability (Ashtari et al. 2020). In India, monitoring expectations are reinforced through regulatory systems: CPCB reporting frameworks emphasise category-wise waste quantification, documentation, and facility-level reporting through annual returns and oversight mechanisms, supporting state-level benchmarking and identification of non-compliance patterns (Central Pollution Control Board 2018). Facility-level monitoring is commonly operationalised through structured checklist-based audits aligned to WHO principles and national quality frameworks (e.g., Kayakalp and NQAS), focusing on segregation infrastructure, signage, PPE use, interim storage conditions, and records; repeated audits with feedback are used to identify recurrent non-

compliances and guide corrective actions (Government of Chhattisgarh 2019). Digital traceability tools (including barcoding mandated under India’s Bio-medical Waste Management Rules) are intended to strengthen accountability and completeness of records across the waste chain; however, published evaluations of hospital-level implementation remain limited, so hospitals often triangulate barcode/record data with direct observation and audit scores to create practical dashboards for continuous quality improvement (Government of India 2016; Ashtari et al. 2020).

**Challenges and Barriers in Biomedical Waste Management:** Despite strong regulatory frameworks, substantial operational and behavioural barriers persist across low- and middle-income settings. Infrastructure limitations such as inadequate colour-coded bins, poorly designed storage areas and malfunctioning autoclaves remain common challenges, as documented by Krishnamoorthy et al. (2022) in Tamil Nadu COVID care facilities. Human-resource constraints also play a significant role. Behavioural barriers such as low perceived risk, absence of safety culture, informal norms and competing clinical priorities are well described in studies from India, Ethiopia and Ghana. Enforcement challenges remain a major barrier to effective healthcare waste management, particularly in low- and middle-income countries. A comprehensive review by Datta et al. (2018) highlighted persistent gaps in supervision, weak accountability mechanisms, inadequate documentation and inconsistent monitoring in Indian hospitals, despite the presence of comprehensive biomedical waste regulations. Similarly, a systematic review by Debere et al. (2014) demonstrated that lack of managerial oversight, poor enforcement of standard operating procedures and absence of regular audits were common contributors to non-compliance in healthcare waste management systems across multiple countries. More recently, Alrabiah et al. (2023), in a large systematic review of hospital waste management practices, emphasized that accreditation and training alone do not ensure compliance unless supported by continuous supervision, structured audit–feedback mechanisms and clear administrative responsibility. These findings indicate that enforcement, rather than regulation alone, is critical for sustaining safe waste-management practices.



**Future Directions:** The evolving landscape of biomedical waste management presents several areas for future innovation. Digital tools including barcoding, RFID-based tracking, mobile audit applications and AI-assisted monitoring offer significant potential for real-time evaluation and reduction of manual errors. Green hospital initiatives, such as energy-efficient autoclaving, decentralised non-burn treatment technologies and reduction of single-use plastics, are gaining prominence globally, supported by sustainability frameworks within tertiary hospitals. Integrating quality-improvement methods with infection prevention and control (IPC) programmes can create synergistic gains, as hospitals increasingly rely on shared human resources, supervisory systems and training platforms. National-level capacity building, through standardised curricula, competency-based assessments and regulatory enforcement, will be essential for addressing workforce variability. Strengthening partnerships between hospitals, Common Biomedical Waste Treatment Facilities (CBWTFs) and state pollution boards will further enhance compliance monitoring and environmental safety.

**Conclusion:** Biomedical waste management remains a critical patient-safety, worker-safety and environmental priority, particularly in tertiary-care hospitals that generate high waste volumes and complex waste streams. Global and national evidence shows that gaps in segregation, PPE use, transport, storage and occupational safety persist despite well-defined regulatory frameworks. Continuous training, behaviour-focused interventions, ongoing supervisory audits and digital innovations are central to strengthening compliance. Integrating quality-improvement models with routine hospital processes can enhance sustainability and improve safety outcomes. Tertiary-care settings, with their diverse waste streams and high patient turnover, represent priority institutions for targeted investments in monitoring, capacity building and system redesign.

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