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Review on Medical Waste Management in India Current Status Challenges and Future Prespective

Yogita Nandkishor Sharma[1], Dr. Shivshankar D Mhaske[2], Shatrughna U. Nagrik[3]
Students, Satyajeet College of Pharmacy, Mehkar, Buldhana, Maharashtra[1]
Principal, Satyajeet College of Pharmacy, Mehkar, Buldhana, Maharashtra[2]
Professor, Satyajeet College of Pharmacy, Mehkar, Buldhana, Maharashtra[3]

Abstract: *The management of biomedical waste has become a major concern of public health and environmental concern in India, which is explained by the growth of medical activities and the development of medical infrastructure. Biomedical waste refers to any form of waste produced in the process of diagnosis, treatment, or researching of biological materials and relates to high levels of infectious and chemical risks unless it is properly handled. Currently India generates more than 600 tons of biomedical waste on an average day and this number is rising as the population grows, modernization in healthcare is taking place, and more people are using disposable medical products. The COVID -19 pandemic also increased the production of wastes due to the widespread use of personal protective equipment, test materials, and vaccination disposables. The existing evidence shows that the promulgation of the Biomedical Waste Management Rules of 2016 and its amendments have resulted in the improvement of regulatory frameworks. These initiatives have enhanced segregation standards, the use of barcoding systems and the need to have an ecologically friendly environment in disposal. However, there are still significant problems such as the inadequate segregation at the source, disproportionate distribution of treatment facilities, lack of sufficient training of the healthcare workers, lack of capacity to enforce it and inadequate practices of disposal in rural and peri-urban areas. These inadequacies lead to pollution of the environment, workplace dangers to waste handlers and increased risk of contracting diseases. The future directions emphasize the need to strengthen regulatory enforcement, improve infrastructure of treatment, improve segregation practices and incorporate digital tracking technologies. The implementation of non-burn treatment systems, increasing the training programs, and community sensitization efforts are critical towards reducing the environmental and health effects. Long-term policy planning should be informed by sustainable methods based on the principles of the circular economy, i.e., including safe recycling, minimization of waste, and responsible use of resources.*

Keywords*:* Biomedical waste in India includes healthcare waste and requires effective management practices. There are several challenges in this area, along with a complex regulatory framework

I. INTRODUCTION

Medical or biomedical waste is one of the most vital by-products of modern healthcare systems that pose a high threat to the state of health as well as to the environment when not properly managed. The blistering development of medical facilities worldwide, the increase in the amount of patients, and the growth of the utilization of the disposable healthcare products have caused the significant growth in the dangerous healthcare waste, in the developing countries in particular in India. Thus, proper management of medical waste has become an essential element of sustainable population health, regulatory provisions, environmental management and prevention and control of infections.

Definition of Medical/Biomedical Waste

Biomedical waste (BMW) is any waste that is produced as a result of diagnosing, treatment, immunisation of humans or animals, research or making and testing of any biological substance. The World Health Organization (WHO)

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estimates that approximately 15 percent of all healthcare waste can be categorised as being hazardous, encompassing infectious, toxic or radioactive materials, and thus has to be handled, treated and disposed specially to reduce the negative health and environmental outcomes [1]. In the Indian setting the Biomedical Waste Management Rules (2016) define biomedical waste to mean all waste generated by a healthcare facility (HCF) that includes a hospital, clinic, laboratory, blood bank or research institution, which is likely to contain blood, body fluids, chemicals, pharmaceuticals or pathogenic agents [2]. This group includes various materials, such as sharps, pathological waste, microbiological cultures, cytotoxic drugs, chemical waste, discarded medical devices, and, most recently, plastic based disposables such as personal protective equipment (PPE) and syringes. The medical waste is so heterogeneous and hazardous that it requires strict segregation at the point of origin, proper collection, safe storage, safe transportation and scientifically proven protocols of treatment. Poor management at any level increases exposure to pathogenic microorganisms, sharps and toxic pollutants produced under unsafe disposal methods like open burning. As such, the definition and classification of biomedical wastes is the basis of creating organized and legally acceptable management systems.

Global Context and Relevance to Public Health and Environment

Medical waste production has been rising all over the world due to population development, development of new and improved technologies in healthcare, and an increased use of single-use medical products [3]. The World Health Organization estimates that the amount of healthcare waste produced by healthcare facilities globally every year total to millions of tonnes, most of which is hospital and diagnostic waste. Despite the fact that high-income nations generate higher amounts of waste per bed, the low- and middle-income nations (LMICs) typically face inadequate treatment technologies, poor segregation patterns, and ineffective enforcement of their regulations [1].

Poor handling of medical waste is associated with severe health issues to the people. As a case in point, sharing of contaminated syringes and poor sharps disposal support the spread of blood-borne diseases, including but not limited to, hepatitis B, hepatitis C, and HIV. Unsafe injections alone are estimated by the World Health Organization to claim about 1.3 million deaths each year across the world [1]. People who deal with waste, do medical care, sanitation, and informal waste collection are especially susceptible, often due to the absence of protective gear or necessary education.

There are also serious environmental impacts. Medical wastes disposed into the environment through incineration without emission control results in release of toxic pollutants, such as dioxins, furans and particulate matter, which cause cancer and endocrine disruption [4]. The extraction of chemicals and pharmaceuticals through the landfills into the soil and ground water also poses more ecological risks. Medical waste contains plastics that are the cause of microplastic contamination and radioactive waste which causes environmental hazards in the long term unless well contained.

These global issues were increased by the COVID-19 pandemic. The resulting large volumes of personal protective equipment, testing material and disinfectants led to a situation of unparalleled amounts of infectious waste, flooding current systems, especially in LMICs [5]. Therefore, international medical organizations have emphasized the need to have integrated, circular, and eco-friendly approaches to medical waste management.

India’s Healthcare Expansion and Rising Waste Generation

The healthcare sector in India has undergone a tremendous increase in the last twenty years characterized by an increase in the number of hospitals, laboratory diagnostic centres, primary health centres and privately owned clinics. This growth has also increased the size of the biomedical waste produced. According to the Central Pollution Control Board (CPCB), more than 600 tonnes of medical waste is produced daily in India by registered medical establishments, and this figure is supplemented by other sources of medical waste of unregistered or informal establishments [6]. The rate of waste production also differs significantly in all states, as it is dependent on the healthcare facilities, the number of people and the urbanisation rates.

The Ayushman Bharat, National Health Mission, the increase in the number of medical colleges, and the extension of the private healthcare chains have also led to the higher use of the service and, thus, higher waste production.

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Additionally, single-use medical products, including syringes, gloves, masks and IV sets, have contributed to increasing volumes of plastic waste to the overall waste stream. The COVID 19 pandemic produced peak levels never witnessed before, with reports of 3040 percent increases in daily biomedical waste generation in city centres in the peak months [5].

Waste management practices in India although they exist, exhibit high disparities in spite of the fact that there is a regulatory framework. Large cities usually have access to Common Biomedical Waste Treatment Facilities (CBWTFs) that have incinerators, autoclaves, and shredders, but in rural regions and small towns, the infrastructure is not sufficient and people have to use the deep burial or unsafe disposal techniques [7]. The separation of the sources is not always consistent, often decontamination of the general and hazardous waste is not observed, this can be explained by the lack of awareness, absence of training as well as human resources.

The informal sector also contributes a lot to the waste system in India. Medical plastics recycling, scavenging and unregulated dumping have been reported in various areas and this has been dangerous to health and the formal waste management systems [8]. Therefore, the emerging issues of healthcare waste in India are strongly associated with the lack of governance, structural constraints, and socio-economic intricacies.

Purpose and Scope of the Review

The current review aims at providing a holistic insight into the current situation, issues that are accompanied by it, and future projections of medical waste management in India. It incorporates the national regulatory framework, waste production patterns, the treatment facilities, and field practices to highlight gains, as well as outline the areas that continue to be gaps. Also, the review examines community health and environmental outcomes of poor waste management especially in the context of new health risks like COVID-19.

The paper also outlines critical operational and policy barriers, such as inefficiencies in segregation, infrastructural deficits, fiscal, technological and enforcement gaps. The review compares the practices in India with the best practice models around the world; through this, plausible strategies to improve the situation are outlined and include adoption of non-burn technologies, digital tracking systems, sound training programmmes, and sound waste minimisation strategies.

It is with this bearing in mind that the review attempts to educate policymakers, healthcare administrators, researchers and environmental planners hence building more resilient, secure and sustainable biomedical waste management systems in the future of India.

II. REGULATORY FRAMEWORK IN INDIA

2.1 Evolution of Biomedical Waste Rules

The Indian regulatory system of biomedical waste (BMW) has been significantly enhanced over the last 20 years due to the increased environmental and social health issues. The first detailed statute, the Biomedical Waste (Management and Handling) Rules, 1998, provided the initial statutory provisions in respect of segregation, collection, treatment and disposal of the biomedical waste produced by healthcare facilities (HCFs) [8]. Markedly, such regulations also brought the concept of colour-coded waste sorting, and demanded medical facilities to have permission of State Pollution Control Boards (SPCBs).

These rules were replaced by the Biomedical Waste Management (BMWM) Rules of 2016 and this enlarged the scope of the rules to include vaccination centres, campaigns, AYUSH hospitals, veterinary schools and clinical research units [9]. In 2016, the changes also required barcoding of BMW receptacles, elimination of chlorinated plastic bags, and a tightening of emission standards of incinerators, which were in line with the technological progress and business requirements.

Mechanisms of compliance were strengthened by further amendments of 2018 and 2019. The 2018 amendment brought in an amendment to increase the waste tracking and reporting as the 2019 amendment expanded the responsibility of occupier and shortened the pre-treatment timeframe of laboratory and microbiological waste and made annual training of healthcare staff on waste management procedures mandatory [10]. All these legislative

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improvements are a pointers to the increasing concern that India has toward responsible and clean biomedical waste management.

2.2 Key Provisions

The BMWM Rules offer an organized approach to the handling of biomedical waste by means of segregation, storage, transportation, treatment and disposal. The principle of segregation at the point of generation is the basis, in that it requires waste to be put into colour-coded containers, i.e. yellow, red, white and blue, based on type of hazard [9]. The regulations are that there must be proper collection and short-term storage of waste in specific locations, which shall in no way be stored after 48 hours.

Regarding transportation, the regulations cover the use of labelled, leak-proof, and covered vehicles that are used either by healthcare facilities or by the Common Biomedical Waste Treatment Facilities (CBWTFs) that are authorised. The treatment methods and its disposal should be done by using accepted technologies such as autoclaving, microwaving, incineration, chemical disinfection or shredding as per the type of waste [11].

There is a clear definition of institutional roles.

Central Pollution Control Board (CPCB) The Central Pollution Control Board (CPCB) is charged with the responsibility of national-level monitoring, technical guidelines and compliance reporting.

The State Pollution Control Boards (SPCBs) are tasked to issue authorisations, impose inspections and regulate compliance with standards.

Medical institutions are required to separate waste, have safe handling, record keeping and training.

CBWTF operators should ensure that biomedical waste is treated and ultimately disposed according to the regulatory standards and documentation is preserved to allow audit [12].

All these provisions are aimed at coming up with a unified and scientifically viable waste-handling practices in the country.

2.3 Compliance Status

Despite the improvement in the regulation structure in India, there is still a disparity in the compliance of the different parts of the country. Recent annual reports of the Central Pollution Control Board (CPCB), despite the fact that over 90⁻ percent of registered facilities that generate healthcare waste are officially incorporated under the Biomedical Waste Management (BMWM) Rules, that real compliance varies widely across states [13]. Compliance is generally higher in urban areas with well-established CBWTF (Biomedical Waste Treatment Facilities) infrastructure, and low in rural and remote areas, which often do not have adequate infrastructure nor are they authorised to treat in a manner which is the most optimal.

The main complications in enforcement include a lack of segregation at the source, insufficient training of healthcare staff, flaws in barcoding adoption, and operational limitations that the CBWTFs face, including overloading or small coverage zone [14]. Moreover, medical plastic recycling and recycling loopholes are also informal and these also contribute to gaps in compliance, especially in those states with large patient numbers and weak enforcement capacity.

In addition, common under-reporting, fewer waste audits and a lack of real-time digital monitoring reduces the success of enforcement programs. Improving monitoring systems, increasing the coverage of CBWTF, and increasing the number of trained staff can not be ignored to achieve the ultimate compliance in the diverse, heterogeneous healthcare environment of India.

III. CURRENT STATUS OF MEDICAL WASTE MANAGEMENT IN INDIA

Year	Estimated BMW generation (tones/day)	Source / notes
2007	288	National estimates (literature)
2011	~370	CPCB/aggregated reports
2018	~530	Studies reporting 2007–2018 increase

2020	600 700*	Pre-COVID and partial reporting; surge during pandemic months
2020 2021 (COVID months)	COVID-period reported cumulative ~39,725 tones (May 2020–Mar 2021)	CPCB COVID reports
2022	550 650	CPCB annual reporting and state returns
2023	See CPCB 2023 annual report (state level variances)	Official annual report

3.1 Waste Generation Trends

Color code	Type of waste	Examples
Yellow	Infectious & antimicrobial waste	Human tissues, blood soaked items, expired medicines
Red	Contaminated recyclable waste	IV sets, catheters, syringes (without needle)
White	Sharps waste	Needles,blades, scalpels
Blue	Glassware & metallic implants	Broken glass, medicine vials

India produces high amounts of biomedical wastes annually due to the high rates of healthcare growth, the rise in patient numbers, and the shift to disposable medical materials. Central Pollution Control Board (CPCB) reports that on an average, the country generates more than 600 tonnes of biomedical waste daily with metropolitan cities leading the packs due to the high density of healthcare systems; Delhi, Mumbai, Chennai, and Bengaluru [15]. There are also notable differences in waste generation among the states with Kerala, Gujarat and Maharashtra reporting higher per-bed waste generation because of the well-established healthcare facilities, and states with less prominent facilities, such as Bihar and Jharkhand, have lower waste generation but experience more difficulties with its management [16]. There is a very obvious difference between urban and rural healthcare facilities. The urban centres generally generate more biomedical waste but can also receive more treatment facilities and regulatory control. Conversely, the rural healthcare locations, such as primary health centres, rural hospitals and sub-centres, produce lesser volumes but they usually lack an adequate segregation, storage, and treatment systems thus leading to poor disposal in open places or municipal waste streams [17].

3.2 Segregation and On site Handling

The most important phase of biomedical waste management is segregation at the source. Regardless of the clear regulatory requirements, the effectiveness of segregation is not evenly spread among the healthcare facilities. The reports of the Central Pollution Control Board (CPCB) show that in spite of the fact that a great number of hospitals accredited may be located in cities, the most of the small-sized clinics and centres in the country do not separate the infectious and general waste, as a result of the lack of knowledge or limited personnel steps [15].

The use of colour-coded containers, as described in the Biomedical Waste Management Rules (yellow, red, white and blue), is usually adequate in the larger hospitals; nevertheless, in smaller facilities, especially in the semi-urban and rural areas, this method is not sufficient. Moreover, there are still gaps in training; high turnover of housekeeping staff and insufficient refresher training are some of the reasons that lead to the re-appearing of lapses in waste -handling practices [18].

3.3 Treatment Infrastructure

In India, the biomedical waste disposal system is characterized largely by Common Biomedical Waste Treatment Facilities (CBWTFs) that are the providers of central treatment modalities; incineration, autoclaving, and shredding. The latest CPCB statistics show that over 200 CBWTFs are operating, with a heavy concentration towards urbanised and industrialised states [19]. Such centres are critical in protecting the environment and the general health of the population because they enable the safe disposal of waste produced by unfathomable healthcare centres.

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Yet, there are still great regional inequalities. States in the northern and western regions of the country also have a relatively strong dispersion of CBWTFs, but a significant portion of northeastern and rural jurisdictions is underserved, forcing them to either use on-site treatment modalities or deep burial wells, which are often poorly designed and poorly monitored [20].

Autoclaves, microwaves processing unit, chemical disinfection plans, and a small fraction of hospital scale incinerators, on-site treatment units are only commonly found in large tertiary care facilities. However, in contrast, deep burial practices prevail in the rural community, but are authorised in specific regulatory conditions, however, they are often misused due to the lack of alternative approaches [21].

3.4 Disposal Practices

Method	Type of waste treated	Purpose
Incineration	Anatomical, infectious waste	Volume reduction, pathogen destruction
Autoclaving	Plastic and microbiological waste	Sterilization
Microwaving	Moist infectious waste	Disinfection
Shredding	Plastic waste	Prevents reuse
Chemical disinfection	Liquid waste	Neutralization
Plasma pyrolysis	Hazardous medical waste	High temperature destruction
Deep burial	Rural infectious waste	Safe land disposal

Such practices in treatment and disposal differ according to the type of waste and infrastructure available. Incineration is still widely used in anatomical waste, contaminated plastics, and microbiological waste despite ongoing controversies about the release of emissions as a result of the inefficient or outdated incinerators [22]. A large scale use of autoclaving and microwaving of infectious waste is adopted and application of chemical treatment is used in liquid waste and laboratory effluents. After the disinfection, shredding is done to make waste inappropriate to be used.

After treatment, the residual wastes like incinerator ash, treated plastics and sharps are disposed or sold to a recycling stream in regulated landfills as per the set standards. However, the dumping of ash remains an issue, with various areas reporting the inefficient control of landfills, therefore increasing the chances of soil and water pollution [23].

3.5 Impact of the COVID 19 Pandemic

The COVID-19 pandemic changed the situation with biomedical waste in India significantly. Production of waste rose by 3040 per cent daily, particularly in isolation and diagnostic units, and with the extensive use of personal protective equipment (PPE) [24]. This sudden increase put a lot of stress on biomedical waste treatment facilities (CBWTFs) available to most of which were near or even beyond their designated capacity.

The Central Pollution Control Board (CPCB) as a reaction to this issued special instructions regarding the processing of COVID-19 wastes that obliged different labeling of the waste, setting aside of separate collection tracks, use of a faster treatment schedule, and enhancement of reporting systems through the COVID-19 Biomedical Waste Tracking Application [25]. Nevertheless, a significant percentage of plants still had to deal with logistical challenges, including delayed collections, full capacity of treatment units, and increased operational spending.

The pandemic highlighted the need to have resilient waste management infrastructures that could handle the increased infectious waste and the importance of having digital monitoring systems, decentralized treatment technologies, and continuous training of the staff.

IV. ENVIRONMENTAL AND PUBLIC HEALTH IMPACTS

4.1 Air, Water, and Soil Pollution

When poorly disposed or improperly processed, biomedical waste poses a significant threat to the environment. Incineration is one of the mostly used modalities of treatment in India, but when it lacks adequate emission control systems, it may release dangerous substances- such as dioxin, furan, heavy metals and particulate matter- [26]. These are the long-lasting organic pollutants which are known carcinogens and the pollutants can be transferred to a great distance through atmospheric deposition thus contaminating the ecosystem and entering the food chain.

Unhealthy disposal habits, including open burning, unsound deep burial, and dumping of untreated waste are some of the causes of soil and groundwater contamination. The leachates of the pharmaceutical, chemical, and pathological waste materials present in the discards are found in soil and water sources thus disrupting the microbial balance, weakening aquatic organisms, and reducing crop productivity [27]. Empirical studies in various Indian cities have indicated that there are high levels of pathogens, toxic metals, and microplastics near dumping locations whereby biomedical wastes have been mixed with municipal waste products [29].

These kinds of environmental pollution particularly in rural and peri-urban areas that do not have strong waste management systems increases ecological health hazards in the long run and erodes the ecological sustainability.

4.2 Occupational Health Risks

Biomedical wastes are serious occupational hazards to the workers who have direct or indirect involvement in the healthcare and waste management. Individuals exposed to waste management, sanitarians, hospital housekeeping, and informal waste collectors are some of the high risk groups because they often deal with infectious substances, sharps, and chemicals [29]. Sharps injury is one of the most common risks, which is likely to support the transmission of the bloodborne pathogens, including hepatitis B, C, and HIV.

Healthcare workers also face risks in the absence of the observance of the segregation procedures or deficit of personal protective equipment. The waste handling or treatment can result in the aerosols that expose their staff to respiratory pathogens and toxic chemicals. According to WHO estimates, in the global context, the percentage of work-related infections can be successful in terms of improper use of contaminated sharps and infectious waste [30].

Lack of proper training, use of personal protective equipment, and heavier loads in the overworked health centers all exacerbate the susceptibility of frontline workers in India.

4.3 Community Health Risks

Poor handling of biomedical wastes has a disastrous effect on the neighboring communities. The recycling of contaminated polymers illegally is one of the primary concerns, and in this process, informal litter collectors use retrieval procedures of discarded syringes and intravenous tubing, and plastic containers in unauthorized dumping areas. The further trading of the materials to informal recycling organizations and their reentry into commercial supply chains once again increase the risk of infections among both the consumers and occupation groups [31].

The haphazard dumping of the biomedical waste near the living areas exposes the locals to unpleasant smell, disease carriers, and pathogens. Small mammals, arthropods, and stray fauna can serve as mechanical vectors, which carry contaminants of dumping sites into the domestic environment, enhancing cases of gastrointestinal infections, dermatologic and respiratory illnesses [32]. In addition, children that play around open dumps are exposed to increased risks of using sharp tools and contracting pathogenic organisms.

The populations living in close areas of landfills or incineration plants can simultaneously be exposed to pollutants of the air and water contamination of the aquifers, thus, promoting chronic pathological processes. Lack of public education, poor enforcement of regulations, and lack of waste segregation are all examples that maintain the existence of these community-level hazards.

V. CHALLENGES IN CURRENT MEDICAL WASTE MANAGEMENT

5.1 Inadequate Segregation and Training

Poor segregation at the point of origin is one of the most endemic issues of the Indian system of biomedical waste management. Despite the strict colour-coded segregation in Biomedical Waste Management Rules, there are still numerous healthcare facilities (especially small clinics, diagnostic centres, and rural hospitals) that do not separate infectious, recyclable, and general waste as there is lack of awareness and staff training [33]. The high housekeeping staff turnover and inconsistent training are also very weak in upholding the practice of segregation. Research shows that failure to comply with the segregation regulations tends to lead to greater amounts of waste that need a specialized treatment method hence putting a strain on the treatment facilities and the likelihood of occupational exposure [34].

5.2 Infrastructure Gaps

In India, there exists a high level of infrastructural imbalance in the management of biomedical waste. Although large urban centres have a good coverage of Common Biomedical Waste Treatment Facilities (CBWTFs), the rural and remote regions do not have access to centralized treatment systems. This shortage forces them to use deep burial pits or open burial which often do not meet the regulatory standards [35].

States with topographic features like hilly geography or scattered residents including the Northeast states face a great challenge towards the initiation and continued support of CBWTFs. These limitations are associated with the logistic difficulties and financial limitations which hamper the construction of efficient, centralized waste-management systems.

Therefore, healthcare institutions located in underserved areas have a consistent problem with inability to comply with safe treatment and disposal standards, thus threatening to undermine the health and environmental protection of the population.

5.3 Financial and Operational Constraints

Bio medical wastes treatment systems such as incinerators, autoclaves and barcoding systems are costly and pose significant financial limits to the public health institutions, especially small and medium size units.

Many government hospitals work under limited financial budgets limiting their ability to maintain their facilities in time, upgrade their equipment, and acquire advanced treatment facilities [36].

In addition, operational costs such as electricity, staff salaries, and special transportation also increase the pressure on the budget. Community-based waste treatment plants are faced with strain in the finances when providing services in low-density regions where the amount of waste is low to continue operating.

5.4 Monitoring and Enforcement Issues

In most jurisdictions, even with a well-developed regulation framework, the effectiveness of monitoring and enforcement is lacking. The State Pollution Control Boards (SPCBs) also often face the lack of qualified staff, which limits their ability to perform routine inspections and audits of health care facilities (Agrawal, 2021)[37]. Moreover, the lack of uniform, or ad hoc, reporting of healthcare establishments worsens the state of oversight. National implementation, despite the improved traceability brought about by digital solutions like barcoding, is still heterogeneous, even though it has led to improved traceability in some states. As a result, loose enforcement creates a gap where failure to comply goes unpunished and unsafe disposal is triggered and environmental violations are committed.

5.5 Informal Sector Involvement

India has a large informal recycling industry that is a part of the waste management system. The unregulated collection and recycling of syringes, IV sets and packaging materials that are contaminated with plastics promote significant health risks to the waste pickers and the community at large [38]. Informal recyclers have always worked without either protective equipment or proper disinfection, which increases the risk of spreading infectious diseases.

Additionally, the little incorporation of the informal workers into the formal waste management systems lead to the loss of material traceability as well as interfering with the integrity of the controlled disposal processes.

5.6 Challenges from New Waste Streams

New waste streams are also creating a new burden to the biomedical waste management systems in India. The COVID-19 outbreak caused record amounts of personal protective equipment (PPE) waste, including face mask, gloves, face shields, and disposable gowns to be produced both in healthcare and community contexts [39]. On the same note, pharmaceutical waste, including those that are out of expiry and those that have traces of antibiotics is often disposed of inappropriately without proper segregation or treatment, thus leading to environmental pollution and antimicrobial resistance. The increased use of electronic medical equipment, diagnostic tools, sensors, and monitoring devices has also led to a boom in electronic waste (e-waste) that requires specialized handling and disposal practices that are not easily done by most health facilities [40]. These new types of waste require new regulatory frameworks, new technologies and better training in order to guarantee safe and sustainable management.

VI. GLOBAL BEST PRACTICES AND LESSONS FOR INDIA

Empirical studies on the management of biomedical waste (BMWM) in the world offer invaluable information on the optimization of the current management systems in India. Several jurisdictions have proven to use stringent regulatory frameworks, state-of-the-art treatment methods, and electronic tracking systems that in total encourage safer, more efficient, and sustainably waste disposal methods.

6.1 WHO Recommendations

World Health Organization (WHO) publishes detailed principles regarding the safe management, treatment, and disposal of biomedical waste, which highlights that segregation should commence at the generation point, avoidance of combustion techniques, capacity building, and the creation of a sound regulatory system. [41]

WHO recommends a system of waste minimization and recycling with the following level of priorities: reduction of hazardous waste through source control, use of alternative less hazardous methods instead of incineration and continuous training programmes on health-care workers. [42]

The organization also promotes the use of standardized colour-coding systems, personal protective equipment among waste handlers and frequent audits to ensure that the international safety standards are met. [43].

6.2 Examples from the EU, Japan, and Singapore

The example of countries in the European Union (EU), Japan, and Singapore show that highly restrictive laws and modernized infrastructure have a significant positive impact on the safety and effectiveness of medical waste systems.

EU In the EU, biomedical waste management (BMWM) is governed by the directives that focus on waste minimisation, mandatory segregation, and widespread use of non-incineration technologies. Many countries are members of the EU that use advanced autoclaving, chemical disinfection, and steam sterilisation procedures to reduce reliance on incinerators and minimise the emission of dioxins and furans [44].

The Japanese system is a decentralised system that is marked by strong monitoring systems and traceability. Waste generators must record all the phases namely segregation to final disposal using electronic manifests that record real-time waste routes [45]. This will allow minimum spread to informal sectors and enhance accountability.

The Singaporeans embrace an integrated waste management paradigm that is based on centralised and high-efficiency incineration plants and stiff operational requirements. The state is enforcing consistent adherence to both the state and non-state health-care facilities through the routine audit and contracting licensed waste operators with improved treatment facilities [46].

6.3 Advanced Treatment Technologies

There are several technologically advanced, environmentally friendly and high efficient methodologies of treatment that have become known globally. Plasma pyrolysis which is used in Japan and in some parts of Europe is used to decompose waste at higher temperatures of more than 1,200 C and thus producing non-toxic gases and vitrified slag. The product of this process is almost zero emissions and can safely treat mixed and high-risk waste streams [47].

Other non-combustion technologies, which include autoclaves, microwave irradiation, chemical disinfection units and high-temperature steam systems have become the technologies that are more preferred in the world, due to their lower environmental foot print and compliance with international emission regulations [48].

Use of these technologies in India would help to reduce the use of traditional incineration that remains one of the major sources of harmful pollutants like dioxins, furans and particulate matter [49].

6.4 Digital Tracking Systems

Digital waste tracking systems are introduced in many developed governments in order to be more transparent and accountable. Barcoding technologies provide the opportunity to identify waste bags and containers in each step of handling. In some countries, like the European Union or Japan, barcodes which are associated with electronic databases are used to track waste flows, prevent illegal disposal, and confirm that the target is met (see reference [50]).

Vehicle tracking through GPS is another international procedure that maximizes the routing, reduces illegal dumping, and ensures waste goes to treatment facilities. Singapore and South Korea have already managed to implement such systems to check waste transportation in real time (see reference [51]).

Implementing similar large-scale electronic platforms in India would play a significant role in strengthening compliance enforcement, minimizing the embezzlement of reusable resources, and improving the accuracy of the data to use in making evidence-based policies.

VII. FUTURE PERSPECTIVES AND RECOMMENDATIONS

The transformation of the medical waste management system in India through the strategy requires a multidimensional approach that covers the combined elements of policy change, the implementation of modern technology, the improvement of massive infrastructure, and increased publicity. Sustainability, equity, and resilience should be of priority in the future, especially with the growing healthcare demands, and surfacing infectious threats.

7.1 Strengthening Regulations and Compliance

The regulatory system of biomedical waste management in India is quite extensive, but the active implementation and control measures require the expansion.

The creation of a unified national surveillance system that would integrate the state-level systems into a centralized online platform would help to ease the process of equal monitoring and to take corrective actions in a timely manner [52].

The introduction of regular third-party audits, increased levels of transparency, and mandatory digital reporting, through the use of barcoding or GPS-linked solutions, can considerably improve compliance in healthcare facilities [53].

It is essential to increase the capacity of the Pollution Control Boards by having adequate staffing and technical capacity to reduce the regulatory loopholes and reduce delays in enforcing the regulatory process [54].

7.2 Improving Segregation and Training

Safe waste management is still primarily determined by segregation at the point of generation. Errors in waste classification and handling can be decreased by regular capacity building programs for sanitation, waste handlers, and healthcare workers [55]. Curricula in medicine, nursing, and allied health that incorporate biomedical waste management (BMWM) techniques will contribute to the development of a knowledgeable workforce that can follow safe waste procedures throughout their careers [56]. Digital learning resources, real-world examples, and recurring refresher courses should all be included in training modules to ensure competency.

7.3 Technology and Innovation

Utilizing cutting-edge, eco-friendly non-burn treatment technologies like autoclaves, microwaves, plasma pyrolysis, and high-temperature steam systems can lessen the need for incineration and cut down on dangerous pollution emissions [57]. Transparency can be improved and illegal disposal or diversion into unofficial recycling streams can be avoided by utilizing IoT-based tracking systems for real-time waste movement monitoring [58]. Predicting waste generation trends, optimizing CBWTF workloads, and planning infrastructure expansion to meet regional needs are all areas where artificial intelligence (AI) holds great promise [59].

7.4 Infrastructure Expansion

Common Biomedical Waste Treatment Facilities (CBWTFs) are still insufficiently covered in many Indian states. To guarantee that all healthcare facilities have timely access to compliant treatment options, CBWTF networks must be expanded in underserved or high burden areas [60]. Decentralized treatment systems, like small autoclaves or solar-powered sterilizers, can be useful substitutes for centralized facilities in rural, isolated, and hilly locations [61]. Equitable access to safe waste management services will be enhanced by these initiatives.

7.5 Sustainable Approaches

Future plans should put an emphasis on reducing waste at the source by encouraging the use of reusable materials when safe, using disposables sparingly, and enhancing procurement procedures [62]. By implementing a circular economy framework, healthcare facilities can recycle plastics, metals, and glass in a safe and controlled manner, lessening their impact on the environment and conserving resources [63]. To comply with sustainability objectives and international climate commitments, environmentally friendly disposal techniques like engineered landfills, safe ash management, and green incineration technologies must be used [64].

7.6 Public Awareness and Community Participation

In order to lower the risks associated with inappropriate disposal, public involvement is essential, especially in areas close to waste treatment plants or medical facilities. In order to promote community monitoring of disposal sites and increase awareness of safe waste practices, NGOs and local organizations can be extremely helpful [65]. Littering, illegal dumping, and unofficial recycling of hazardous materials can all be decreased with the aid of behavioral change initiatives, such as community campaigns, educational materials, and citizen reporting platforms [66]. Increasing community involvement develops a shared responsibility model that is necessary for long-term viability.

VIII. CONCLUSION

Over the past 20 years, India has made significant progress in managing medical waste, especially since the Biomedical Waste Management Rules (2016) and their updates were put into effect. Healthcare facilities are now more accountable, treatment infrastructure has grown, and segregation practices have been improved thanks to these regulations. There are still large gaps in spite of this advancement. Effective waste management is still hampered nationwide by issues like poor segregation, low awareness among healthcare professionals, a lack of infrastructure in rural and remote areas, and uneven enforcement. The need for systemic changes is further highlighted by the growing amount and complexity of medical waste, particularly in the wake of the COVID-19 pandemic.

India should take a comprehensive approach to ensure sustainable and integrated management of medical waste. India should take a comprehensive approach to ensure best practices are upheld through regulation and compliance, enhancing access to all treatment options to all citizens throughout India and making sure that disposal methods are environmentally friendly. Strategies for sustainable waste management should focus first on reducing "waste" generated by health care services, second on safely recycling and reusing where applicable, and lastly on working collaboratively between government agencies, health care establishments, and communities.

Technology, training, and policy coherence will all continue to play an increasingly important role in ensuring that future medical waste management systems will have a strong emphasis on these areas. Technology-enabled solutions that allow for greater transparency and accountability in medical waste management will become increasingly important, as will increasing the capacity of healthcare workers and waste handlers through repetitive training. Harmonization of waste management policies across different agencies as well as building stronger coordination between agencies with regard to the enforcement of those policies is essential to creating a more robust and sustainable medical waste management system that protects public health and the environment.

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