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EDITORIAL

We feel honoured and privileged to present the Bi-Annual Peer Reviewed Refereed Journal, ISSN (Online): 2583-5203, Volume 4, No. 01, June, 2025 among our esteemed readers and academic fraternity.

This Journal is the outcome of the contributions of insightful research-oriented papers/articles by various eminent academicians, and research scholars in a highly organized and lucid manner with a clear and detailed analysis related to the emerging areas in the fields of Social Sciences and Allied Areas.

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We also express our sincere thanks and gratitude to all the contributors to research papers/ articles who have taken pain in preparing manuscripts, incorporating reviewer(s) valuable suggestions and cooperating with uxs in every possible way.

We also express our heartfelt gratitude to all the esteemed members of the Editorial Board, Esteemed Reviewer(s) who despite their busy schedules have given their valuable time, suggestions and comments to enrich the quality of the contributory resears paper(s) in bringing to light this June issue.

Last, but not least, we revere the patronage and moral support extended by our parents and family members whose constant encouragement and cooperation made it possible for us to complete on time.

We would highly appreciate and look forward to your valuable suggestions, comments and feedback at **editorbr2022@gmail.com**

June, 2025
West Bengal, India

PEMA LAMA
Editor-in-Chief

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RESEARCH ARTICLE

Sustainable Waste Management: Role of AI in Medical and E-Waste Handling

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ABSTRACT

The technology and healthcare industries have rapidly expanded, resulting in a huge surge in the generation of waste, mainly in the form of medical waste and electronic waste. These waste streams pose significant environmental and public health threats across the world. Natural resource sustainable management has increased as a tool to mitigate the negative impacts associated with waste generation and disposal. Identification of the key barriers, innovative solutions, and optimum practices for the sustainable management of medical and technological waste is the objective of this research. The study examines the intricate dynamics of garbage disposal. It identifies tactics, including trash reduction, resource recovery, and circular economy models, based on a careful analysis of the literature, case studies, and supporting data.

This study examines how environmental and socioeconomic factors interact to shape waste management methods and the consequences for accomplishing more general sustainability objectives. The study offers useful information intended to help researchers, industry stakeholders, and legislators create robust and resource-efficient strategies for managing medical and e-waste. By examining existing methods in various geographical and sectoral contexts, this study offers practical suggestions for creating efficient, long-lasting waste management systems.

1 INTRODUCTION

In an age of rapid technological advancement and rising healthcare needs, waste management- particularly medical and e-waste, has become a persistent environmental and public health challenge. In addition to endangering ecosystems and human health, improper disposal of these waste streams exacerbates environmental crises around the world by depleting natural resources. These urgent issues have led to the concept of sustainable resource management, which seeks to highlight the importance of composite approaches that aim to balance the social, economic, and environmental aspects. There are real concerns that the unregulated disposal of e-waste, comprising retired electronic and electrical devices (WEEE), poses to both the environment and human health by containing harmful materials such as poisonous elements and heavy metals. Also, the industry of electronics industry relies on several natural resources, most of which are in short supply. Here, recycling provides a practical solution that makes it possible to retrieve economically worthwhile materials, such as metals, that are abundant in electronic waste (Silveira, 2019). Another, but no less significant, problem is medical waste. Because medical waste contains dangerous substances, improper disposal can be dangerous. Organisational choices and activities to reduce health risks are necessary for effective medical waste management (Insa, 2010). The guidelines and suggestions provided by Chisholm and colleagues (2021) on the sustainable management of medical waste can help legislators create strategies that successfully treat and dispose of trash by incorporating environmentally friendly technology. It facilitates the comprehensive development of policies and health initiatives and promotes collaboration among stakeholders, the legislative, and health systems.

The quantity of medical waste is on the rise due to increased demand for more health facilities. An efficient strategy for healthcare waste management must be implemented to prevent risks to workers' and public health, according to Joshi (2013). For society to develop sustainably, stringent laws are necessary to regulate the use and disposal of natural resources. The continually increasing medical waste has implications for vast areas of influence, including the economy, the environment, and health (Bucătaru, 2021). Healthcare waste contains a huge number of poisonous substances, and unsafe disposal of waste can result in a variety of harm to human and environmental health. In densely populated developing nations, particularly in Asia, poor training and limited resources contribute to poor medical waste management. Ignorance of waste handling exposes workers and the general population to safety and health hazards (Khan, 2019). Biomedical waste, particularly unprocessed sharp items, carries life-threatening viruses like dengue, Hepatitis B, C, and E, infectious diseases such as HIV, etc. In case the waste is disposed of in an improper way, this waste permits germs causing harm to grow in normal waste, leading to both injury and health risks (Chakraborty, 2014). Governments around the globe have realized the need to better manage medical waste and treat it, and it is now a priority for health and environmental protection authorities (Liu, 2021). The secure and sustainable practices disposal of biomedical and electronic trash necessitate comprehensive solutions that include public education, emerging technology, and regulations. E-waste continues to be the most rapidly expanding solid waste industry, and other options such as recycling, landfilling, and exporting are being considered in an effort to minimise the quantity of this toxic waste that is landfilled (Badreya Gharib Khamis Mohammed Alblooshi, 2022). Special attention has been paid to processing biological waste and e-waste, with the 2016 solid waste management (SWM) legislation emphasising handling of this specific waste type (Subhadeep Biswas, 2023).

2 LITERATURE REVIEW

The persistent issue of biomedical waste management affects both affluent and developing nations, with its volume and complexity steadily increasing. There are serious concerns for the ecosystems and health of public health when biomedical waste is not disposed of properly. In both high-income as well as low-income countries, the infrastructure for waste management, such as dumpsters and separate containers, is often found in poor condition, as noted by Manga (2011). Biomedical waste management has garnered attention due to the health risks associated with improper practices. A. Prem Ananth (2010) emphasises that these risks include exposure to infectious agents and toxic substances, which can affect not only humans but also animals and water quality, thereby increasing the risk of disease transmission.

Jade Megan Chisholm (2021) adds that beyond disposal costs, contamination and pollution need to be accounted for when designing systems to store and transport medical waste. Effective healthcare waste management demands a comprehensive and collaborative approach that involves various stakeholders. In developing countries, governments struggle to develop adequate waste management systems due to limited resources (Nouf Sahal Alharbi, 2021). Andrew Jameton

(2002) highlights that reducing environmental impact, ensuring high-quality patient care, and fiscal prudence are essential components of sustainable healthcare. He suggests reducing energy and material consumption in healthcare to minimise pollution and maintain healthy ecosystems. The transition from a waste management mindset to sustainable resource use is a major challenge. T.L. Tudor (2005) argues for a paradigm shift that emphasises waste minimisation at the source and recycling. For such systems to be successful, decision-makers need access to comprehensive information on design, available technologies, and their effects, as stated by G.P.J. Dijkema (2000).

The increasing amount of e-waste worsens the issue, which is a result of society's increased reliance on electrical and electronic devices (EEE). There are severe health and environmental hazards related to the uncontrolled removal of e-waste (Venkatesha Murthy, 2022). The COVID-19 pandemic brought to light the dangers of unchecked trash growth, particularly plastic and e-waste, which have an impact on the environment, wildlife, and human health (Veronica E. Manga, 2011). Rich nations possess the technological know-how and experience necessary to reuse and recycle electronic waste more sustainably, whereas developing nations face major obstacles due to inadequate infrastructure and regulations (Shashi Arya, 2020). Even though there are a few sizable electronic waste recycling amenities, they are inadequate to handle the large volume of electronic waste, and unlicensed recyclers handle 95% of it incorrectly (Mahesh C. Vats, 2014). This highlights how crucial it is to switch to e-waste in a more effective and environmentally conscious way. Based on the above discussion, biomedical and E-waste management require a shift toward sustainable resource use, stronger regulatory frameworks, and a focus on minimising health and environmental risks. The international character of the issue calls for cooperation, creativity, and increased access to information, especially in developing nations where waste management infrastructure is not yet well developed.

3 OVERVIEW OF MEDICAL WASTE: A THEORETICAL FRAMEWORK

Healthcare waste is the waste produced by various medical processes in a hospital, research centre, or laboratory. The remaining 10 to 25 per cent, often known as biomedical waste, is hazardous, whereas the remaining 75 to 80 per cent of trash in the medical industry is nonhazardous and regular rubbish. All of the different kinds of biomedical waste used in medicine are referred to as medical waste. The list of those is as follows: pathogen waste (human tissue, including blood, organs, limbs, fetuses, and other body fluids). Soiled surgical dressings, swabs that come into contact with people or animals that have communicable or pathogenic diseases, contaminated waste from entire isolation units of hospitals, infectious agent stocks, cultures in research labs, dialysis equipment, disposable gowns, aprons, gloves, towels, etc., are examples of contaminated garbage.

Sharp objects include things that can cut, such as scalpels, needles, saws, blades, nails, and cracked glass. Medical waste includes returned-to-ward chemicals, cytotoxic pharmaceuticals, expired medications, and vaccinations. Any solid, liquid, or gaseous chemical that is thrown away after being employed in a laboratory for sterilisation, cleaning, or other purposes is considered chemical waste. Non-toxic substances such as buffer chemicals, inorganic salts, carbohydrates and amino acids; hazardous substances that are combustible, reactive, corrosive, genitotoxic, etc., radioactive waste in pressurized containers and aerosols. Given that biological waste is produced nationwide by pathology labs, dental offices, private medical practices, maternity homes, assisted living facilities, hospitals, and other establishments, it takes on relevance.

4 LINKAGES BETWEEN NATURAL RESOURCES, CLIMATE CHANGE, MEDICAL AND E-WASTE MANAGEMENT

Medical centres produce a variety of waste products, from non-hazardous waste like paper, plastics, and packaging materials to hazardous medical waste like used needles, syringes, and expired drugs. Electrical appliances and medical devices have significant demands on natural resources, including rare earth materials, polymers, glass, and other compounds, in addition to gold, silver, copper, and other metals. Energy-demanding processes are common in the extraction, processing, and production of natural resources, which further contributes to the destruction of the environment. Similarly, e-waste is produced when electronic devices malfunction or wear out. Illegal medical and electronic waste disposal causes landfills to leak greenhouse gases like methane in addition to contaminating the air, water, and soil.

The manufacturing, use and disposal of medical and technological equipment all contribute to global warming in different ways. This covers the amount of energy used in the processes of waste management, production, transportation, and resource extraction. Furthermore, strong greenhouse gases like hydrofluorocarbons (HFCs) and chlorofluorocarbons (CFCs), which contribute to global warming, may be released by various electrical appliances and medical equipment. Sustainable waste management techniques must be used to fight climate change and lessen the detrimental environmental effects of biomedical and electronic waste. This covers tactics like recycling, reusing, reducing trash, and safely getting rid of dangerous materials. The requirement for fossil fuels can be decreased by using waste-to-energy devices to convert electronic and medical waste into fuel.

Regulations and laws are required to make sure that electronic and medical waste is disposed of appropriately and minimise the adverse impacts that it poses on the environment and climate. Medical and hazardous waste handling, processing, transportation, disposal, and treatment are all governed by laws. Additionally, increased producer responsibility laws make electronics makers responsible for repairs when equipment malfunctions. To encourage ethical usage and disposal practices, it is important to raise public knowledge of the effects that medical and technological waste have on the environment and climate. Education campaigns can encourage people and organisations to embrace sustainable practices, including recycling, giving away old equipment, and looking for goods and services that are less harmful to the environment. Researchers can develop strategies to advance sustainability, reduce environmental impacts, and slow down climate change in these crucial areas by examining the relationships between natural resources, climate change, and the management of medical and e-waste. This can guide the creation of tools, processes, and policies that support resource efficiency, climate resilience, and a circular economy in the electronics and healthcare sectors.

5 STANDARD BIOMEDICAL WASTE (MANAGEMENT AND HANDLING) RULES, 1998: AN OVERVIEW

Category 1: Human Anatomical Waste

This category includes body parts, organs and tissues derived from surgical procedures, autopsies, or research activities.

Treatment & Disposal: The recommended methods for disposal are deep burial in designated sites or incineration at high temperatures. Incineration ensures destruction of pathogens and organic matter, while deep burial is permitted in rural areas following strict guidelines.

Category 2: Animal Waste

Waste from veterinary clinics, research amenities, and slaughterhouses, like animal tissues, organs, carcasses, and fluids.

Treatment & Disposal: Incineration is the preferred treatment to avoid the transmission of zoonotic diseases. In certain situations, deep burial under controlled conditions is permitted to avoid environmental pollution.

Category 3: Microbiology and Biotechnology Waste

Biological production waste, toxins, plates, equipment, and microorganism cultures used in research or for medical purposes.

Treatment & Disposal: Autoclaving, microwaving, or proper decontamination is needed to inactivate infectious agents before disposal. Attenuated or live vaccines also require treatment in a like manner before disposal.

Category 4: Waste Sharps

Sharps materials that are injurious and have the potential for infection and include such objects as needles, syringes, blades, scalpels, and shattered glass.

Treatment & Disposal: Autoclaving or microwaving followed by mutilation or shredding makes sharps non-infectious and non-reusable before disposal in special containers.

Category 5: Discarded Medicines and Cytotoxic Drugs

Expired, contaminated, or unused medicines, including cytotoxic drugs employed in chemotherapy.

Treatment & Disposal: Incineration is the method of choice, and the ash so produced is disposed of in landfills with protection to avoid environmental pollution.

Category 6: Blood and Body Fluid Contaminated Solid Waste

For instance, bedding, cotton, dressings, bandages, dirty plaster casts and other objects tainted with bodily fluids or human blood.

Treatment & Disposal: Must be autoclaved or incinerated to disinfect and kill infectious agents before disposal.

Category 7: Solid Waste from Disposable Medical Devices

Such as waste from IV sets, catheters, tubing, and other disposable medical devices.

Treatment & Disposal: Chemical disinfection, autoclaving, microwaving, and mutilation or shredding afterwards avoid reuse and contamination.

Category 8: Liquid Waste

Laboratory process wastewater, cleaning, and disinfection wastewater.

Treatment & Disposal: Chemical treatment is used to neutralise the toxic components before safe discharge into the drainage system.

Category 9: Incineration Ash

Residual ash from incinerated biomedical waste.

Treatment & Disposal: The ash is gathered and disposed of in landfills within municipalities that are capable of safely holding hazardous residues.

Category 10: Chemical Waste

Comprises disinfectants, reagents, and pesticides employed in medical and laboratory environments.

Treatment & Disposal: Chemical treatment is applied in order to neutralise dangerous components. Liquids are discharged into sewers, whereas solid residues are dumped in landfills under protection.

6 AN OVERVIEW OF BIOMEDICAL WASTE MANAGEMENT IN INDIA

Biomedical waste management in India is a major concern for the environment as well as public health, requiring proper procedures for collection, treatment, and disposal. As per the 2023 Annual Report on Biological Waste Management, India has 4,34,966 healthcare facilities (HCFs), out of which 2,97,584 are non-bedded and 1,37,132 are bedded HCFs. These HCFs produce about 743 tons of biological waste per day. Common Bio-Medical Waste Treatment Facilities (CBWTFs) and Captive Treatment Facilities (CTFs) process 694 tons of such waste daily.

There is a deficit in compliance as more than 28.59% of HCFs lack compliance with proper waste management processes, although 71% of them are using CBWTFs and 3.6% use CTFs. India already has 234 CBWTFs and is building an additional 30 to meet the infrastructure requirements. With 20,081 HCFs/CBWTFs that are not compliant with BMW regulations, there are still regulatory issues that have resulted in 8,082 enforcement notifications. To address these issues and ensure effective biological waste management in the country, enhanced regulatory control, better infrastructure, and better data reporting systems are required.

Table 1
AN OVERVIEW OF INDIA'S BIOMEDICAL WASTE MANAGEMENT SYSTEM

Parameter (s)	Number
Total No. of HCFs	4,34,966
No. of Bedded HCFs	1,37,132
No. of Non-Bedded HCFs	2,97,584
Total No. of Beds	30,41,937
No. of CBWTFs	234* + 30**
No. of HCFs Obtained Authorisation	1,44,905
No. of HCFs Utilising CBWTFs	3,10,606
Number of HCFs Having Captive Treatment Facilities	15,870
Number of Captive Incinerators Operated by HCFs	69
Quantity of BMW Generated (tons/day)	743
Quantity of BMW Treated (tons/day)	694
Number of HCFs/CBWTFs Violating BMW Rules	20,081
No. of Show-Cause Notices/Directions Issued	8,082

Note: *Annual Report on Biomedical Waste Management for the Year 2023;*

(Central Pollution Control Board, Ministry of Environment, Forest & Climate Change)

(i)-CBWTFs in operation; (ii) ** - CBWTFs provided in a table under construction https://cpcb.nic.in/uploads/Projects/Bio-Medical-Waste/AR_BMWM_2023.pdf*

Table 2
TRENDS AND CHALLENGES IN BIOMEDICAL WASTE MANAGEMENT (2020–2023)

Particulars	2020	2021	2022	2023
No. of HCFs	3,52,014	3,75,256	3,93,939	4,34,966
No. of bedded HCFs	1,13,186	1,21,396	1,25,259	1,37,132
No. of non-bedded HCFs	2,37,938	2,53,860	2,67,155	2,97,584
No. of beds	2,5,44,116	25,61,295	24,65,063	30,41,937
No. of CBWTFs	208	215* + 35**	218* + 34**	234* + 30**
No. of HCFs utilising CBWTF	2,44,282	2,62,786	3,10,809	3,10,606
No. of HCFs obtained authorisation	1,60,736	3,20,751	1,56,637	1,44,905
Number of HCFs having Captive Treatment Facilities	17,206	13,605	17,490	15,870
Number of Captive Incinerators Operated by HCFs	125	102	153	69
Quantity of BMW generated (Tons/day)	774	764 (684 Non-COVID BMW + 80 COVID BMW)	705	743
Quantity of BMW treated (Tons/day)	708	721	645	694
Number of HCFs/CBWTFs violated BMWM Rules, 2016	22,261	23,199	22,306	20,081
Number of Show-cause notices/Directions issued to defaulter HCFs	13, 389	15,355	8,291	8,082

Note: Annual Report on Biomedical Waste Management for the Year 2020-23;

(Central Pollution Control Board, Ministry of Environment, Forest & Climate Change)

(i)-CBWTFs in operation; (ii) ** - CBWTFs provided in a table under construction https://cpcb.nic.in/uploads/Projects/Bio-Medical-Waste/AR_BMWM_2023.pdf*

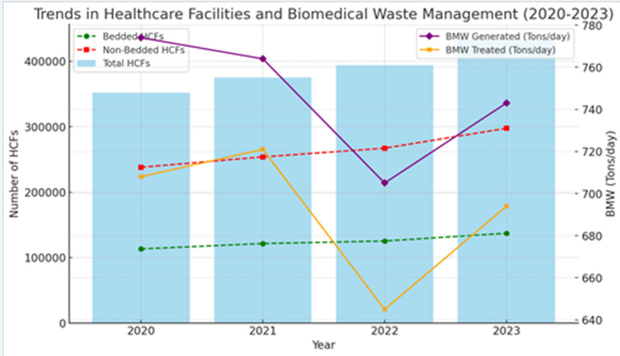
The 2020 - 2023 biomedical waste management (BMWM) comparison highlights the principal trends in waste generation, treatment effectiveness, compliance with regulation, and healthcare infrastructure development. The total healthcare facilities (HCFs) had increased steadily from 3,52,014 in 2020 to 4,34,966 in 2023, with both bedded and non-bedded HCFs contributing to it. There are issues about compliance with regulations, though, as regulated HCFs had a poor decline after 2021. From COVID-19 waste, the generation of biomedical waste varied, reaching a high of 774 tons per day during the year 2020, decreasing over the following years, then increasing again to 743 tons per day in 2023. The same pattern was observed for waste treatment capacities, indicating shifts in processing effectiveness.

Common Biomedical Waste Treatment Facilities (CBWTFs) are increasing, while captive treatment facilities and incinerators are decreasing, reflecting a shift towards centralised waste management. Incremental improvement in compliance with regulations could be seen, as the count of BMWM Rules, 2016 violations reduced from 22,261 during 2020 to 20,081 in 2023. Additionally, there were many fewer show-cause notices issued to HCFs that were not complying. These trends indicate enhanced policy-based biomedical waste management practices as well as improved enforcement procedures.

While there has been general progress in waste management infrastructure and regulatory performance, there are problems with sustaining authorisation levels, attaining consistent waste treatment efficacy, and reinforcing enforcement mechanisms that remain. Policy reforms, continued treatment infrastructure spending, and improved BMWM regulation enforcement are all needed for future sustainable biomedical waste management.

Figure 1

TRENDS IN HEALTHCARE FACILITIES AND BIOMEDICAL WASTE MANAGEMENT (2020–2023)



The trends in healthcare facilities and biomedical waste (BMW) management from the period 2020 - 2023 are analysed to determine the most notable developments in waste generation patterns, infrastructure development, and regulatory compliance.

Expansion of Healthcare Facilities: As healthcare transitioned towards ambulatory and decentralised models, the total number of HCFs increased steadily from 352,014 in 2020 to 434,966 in 2023. Non-bedded HCFs increased at a faster rate.

BMW Generation and Treatment: BMW production reached its peak since COVID-19 in 2020 at 774 tons per day. It decreased to 705 tons per day in 2022 but increased to 743 tons per day in 2023. Nevertheless, waste output surpassed treatment capacity, particularly in 2022, which reflects waste processing deficiencies

Shift towards Centralised Waste Management: There is a recommendation for a transition to centralised waste treatment systems reflected in the growth of CBWTFs (from 208 in 2020 to 234 in 2023) and the reduction in captive treatment plants and incinerators.

Trends in Compliance with Regulations: BMWM Rules, 2016 violations gradually reduced from 22,261 in 2020 to 20,081 in 2023, and show-cause notices also declined enormously, indicating increased enforcement and compliance.

The findings reflect that although healthcare infrastructure continues to grow, problems regarding

BMW treatment capacity persist. Future projects should focus on enlarging BMW processing plants, rationalising legal frameworks, and ensuring environmentally safe ways of disposing of waste.

7 ROLE OF AI SUSTAINABLE MANAGEMENT OF BIO-MEDICAL WASTES

One pioneering move in the direction of environmental conservation and sustainability is using artificial intelligence (AI) for sustainable biomedical waste management. Handling biomedical waste, which is essential as it is hazardous to the environment and human health, has been challenging in multiple ways, especially after the COVID-19 pandemic led to the exponential increase in production of waste (Sengeni et al., 2023). AI plays a multi-faceted role in the resolution of these issues in terms of process optimisation, waste minimisation, and better decision-making, which all work together to reduce the environmental footprint of medical waste disposal. Through waste classification, collection and disposal procedures, artificial intelligence (AI) technologies have a particularly significant impact on biomedical waste management.

Artificial intelligence (AI)-driven improvements like truck route optimisation, waste bin level detection, and waste characteristic predictions have increased operational efficiency and decreased contamination concerns. AI, for instance, can forecast trash classification and waste generation trends, enabling more precise resource allocation and planning. In addition to increasing productivity, this predictive ability facilitates the shift to circular economy (CE) models, which see waste as a resource rather than a byproduct and ultimately help create a more sustainable future (Velibor, 2023). A significant advantage of artificial intelligence in this context is its ability to automate and rationalise processes. Automatic learning algorithms, for example, are used to sort waste with high precision, separating recyclable materials from toxic materials, thereby minimising the contamination of recycling flows. Sensors based on artificial intelligence, combined with the Internet of Things (IoT), constantly monitor waste filling levels. This allows you to delete data in real time. This real-time information allows dynamic vehicle routing to collect costs and ensure effective distribution of resources and low-carbon regions.

Moreover, AI contributes to reducing the total volume of waste generated by improving waste processing. Automated systems, equipped with sensors and AI algorithms, can analyse waste as it is deposited and direct it to the appropriate disposal system, whether for recycling, incineration, or landfill. These technologies support the principles of the circular economy by recovering value from waste streams and minimising the need for new resources. However, while AI offers substantial benefits for sustainable biomedical waste management, it also presents challenges. The implementation of AI systems is often complex and requires reliable data, advanced technical infrastructure, and compliance with strict regulatory standards, which can be particularly challenging in developing regions like India. Ethical consequences, especially about data protection and the possibility of moving human work, must also be considered to guarantee that artificial intelligence solutions are responsible and rightly implemented. AI shows a significant role in the promotion of sustainable treatment of Biomedical waste through greater efficiency, minimising waste and the practice of the circular economy. AI greatly lowers the environmental risks associated with biomedical waste and health issues by automating, predicting, and optimising procedures. To increase the possibility of guaranteeing a permanent future, however, the successful application of AI in this field needs to be carefully examined in terms of technological, ethical, and moral challenges.

Table 3
BIOMEDICAL WASTE - KEY ASPECTS

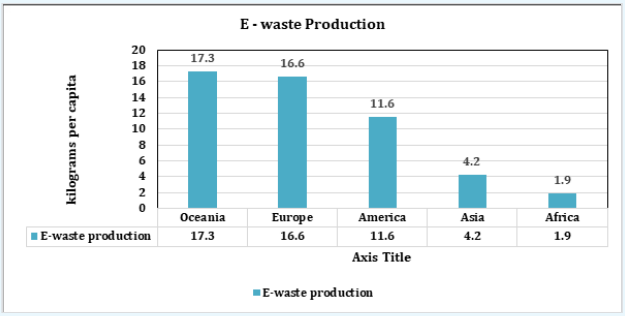
Aspect	Description	AI's Contribution
Waste Segregation and Categorisation	Accurate sorting of biomedical waste into appropriate categories such as hazardous, infectious, recyclable, and general waste.	AI-powered systems use machine learning to precisely analyse waste, ensuring accurate segregation and reducing contamination in recycling streams.
Waste Forecasting and Analytics	Predicting waste generation trends to better manage waste collection, processing, and disposal.	AI analyses historical data to forecast waste characteristics, enabling better planning, resource allocation, and inventory management.
Real-Time Monitoring and Collection	Continuous monitoring of waste bin levels to optimise waste collection schedules and reduce unnecessary trips.	IoT sensors connected to AI platforms provide real-time data, enabling dynamic route optimisation and reducing fuel consumption and emissions.
Circular Economy and Waste Reduction	The transition of the linear to a circular economy by treating and extracting the precious materials of biomedical waste.	AI identifies recyclable materials and automates sorting, contributing to resource recovery and minimizing the amount of waste sent to landfills or incineration.
Automated Waste Handling	Use of robotics and automated systems to handle, transport, and dispose of biomedical waste with minimal human intervention.	AI-powered robotics assist in safe waste handling, reducing human exposure to hazardous materials, and increasing the efficiency of waste sorting and disposal.
Future Prospects	The evolving role of AI in biomedical waste management as technologies advance.	AI is anticipated to contribute significantly to the enhancement of waste management systems around the world by further enhancing automation, efficiency, and sustainability.

8 E-WASTE AND ITS ENVIRONMENTAL IMPACT

Electrical devices that have outlived their usefulness or are no longer required are referred to as e-waste or electronic garbage. E-waste is defined by the UN as "any electronic product that contains potentially harmful substances such as lead, arsenic, cadmium, and mercury that, if not disposed of properly, could cause significant harm to human health and the environment." Globally, only 17.4% of the 57.4 million tons of e-waste generated in 2021 were collected, treated, and recycled. This alarming rate highlights the need to address the growing e-waste problem. Due to the dangerous content that it has, e-waste is particularly troublesome. E-waste is particularly problematic due to the dangerous elements it contains. Improper disposal methods, including acid baths and open burning, which are widespread in illegal recycling practices, can release harmful substances into the environment, including mercury, lead, and polychlorinated biphenyls (PCBs). By emitting toxic compounds into the air, water, and land, the practice has the potential to cause long-term human health and ecological harm. Employees exposed to such processes risk serious diseases such as cancer, neurological damage, miscarriages, and lowered mental abilities, as Anjani R.K. Gollakota (2020) posits.

E-waste production differs greatly by region, capturing variations in consumption behaviour, technological take-up, and waste management capacity:

Figure 2
E-WASTE PRODUCTION BY REGION (KILOGRAMS PER CAPITA)



Source: *The Global E-waste Monitor (2017)*

(https://ewastemonitor.info/wp-content/uploads/2020/11/Global-E-waste-Monitor-2017-electronic-spreads.pdf)

While e-waste generation is global in scale, it is largely uncollected and not disposed of in a responsible manner. This has contributed to environmental accumulation of toxic and non-biodegradable material, polluting the air, water bodies, and land. It also hinders the recycling of precious materials such as precious metals, which are usually dumped together with toxic materials.

9 SUSTAINABLE APPROACHES TO E-WASTE MANAGEMENT

The recycling of precious materials from electronic components is one of the initiatives that tackle the issue of e-waste. For example, heavy metal sludge and other hazardous waste from the electronics industry can be utilised as a substitute fuel for the cement manufacturing process (Yong, 2019). To aid in resource recovery and waste reduction, the leftovers from such activities can be repurposed as raw materials for cement manufacturing. However, the overall effectiveness of hazardous e-waste handling is relatively moderate, despite the great economic and environmental benefits of such activities. Governments, businesses, and consumers must all work together to handle e-waste properly. To guarantee that more electronic trash is recycled and repurposed safely, active engagement is required, as is sufficient education on the risks connected to inappropriate e-waste disposal. Furthermore, new technologies like AI-based trash management systems may be crucial in improving the efficiency of e-waste processing, lowering environmental impacts, and advancing the circular economy.

10 CHALLENGES AND FUTURE DIRECTIONS IN AI-BASED HEALTHCARE WASTE MANAGEMENT

There are many challenges to AI-based healthcare waste management, such as differences in data quality among institutions, exorbitant costs of implementation, challenges to compliance with regulations, cybersecurity threats, and the necessity of technical expertise to operate AI-based systems optimally. Future studies should be aimed at developing standardised datasets to improve model performance and interoperability to bridge these challenges. Lean models and cloud-based deployments are two instances of cost-effective AI solutions that could make implementation feasible in low-resource situations. In addition, to ensure sustainable waste management,

AI can be integrated with circular economy principles to maximise recycling, sterilisation, and waste-to-energy conversion. To enhance operational efficiency and safety, AI-supported real-time monitoring systems can enhance the detection of toxic waste leaks and garbage collection inefficiency. Ethical AI paradigms also need to be investigated in response to job loss and environmental issues. AI-supported waste management systems can also be protected against hackers through the reinforcement of cybersecurity via federated learning and blockchain. Lastly, policymakers can predict waste trends and suggest regulatory enhancements for more efficient and sustainable healthcare waste management strategies with the help of AI-based decision support systems.

11 CONCLUSION

Overall, the mitigation of the threats that medical and technological waste represent to humans and the environment can only be achieved through sustainable healthcare waste management. AI is revolutionising this field by providing effective trash disposal, recycling, and segregation solutions. AI makes it possible to accurately sort medical waste, identify reusable materials, and optimise collection routes to lower carbon emissions through machine learning, robots, and predictive analytics. Additionally, by prolonging the life of medical devices and encouraging appropriate disposal methods, AI-driven solutions aid in the monitoring and reduction of e-waste. When taken as a whole, these developments support a safer, cleaner healthcare system that supports international sustainability objectives.

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