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From Waste to Smart Transformations: AI-Driven Biomedical Waste Management

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Abstract: Introduction: Biomedical waste (BMW) management is crucial for mitigating environmental and human health risks. Conventional methods, which include segregation, collection, transportation, and disposal, often fail to address the growing volumes of waste and the associated hazards. Aim: This article examines existing regional and worldwide practices, trends, challenges and the way forward in BMW management. Methodology: Peer-reviewed publications, conference papers, systematic reviews, and reports published in English that were searched using databases such as PubMed and Google Scholar were among the sources of information that were been synthesized in this review. Search terms included "waste management," "medical waste management," "smart bins," "AI," "machine learning," and "IoT." Results: Globally, disparities in BMW management practices persist, influenced by socio-economic conditions, regulatory frameworks, and resource availability. Developing regions often lack adequate infrastructure, leading to improper waste segregation, unsafe transportation, and open dumping, thereby exacerbating health and environmental risks. With approximately 75–90% of BMW being non-hazardous and the remainder requiring specialized handling, technological advancements. In India, for instance, it generates 1.5–2 kg of waste per bed daily, with an additional surge during the COVID-19 pandemic. Conclusion: Emerging AI-enabled solutions, such as smart bins, real-time monitoring, route optimisation, and blockchain technologies, demonstrate the potential to enhance efficiency, safety, and sustainability in BMW management. From Waste to Smart Transformations, AI-driven biomedical waste management has become a critical necessity at the global and regional levels, underscoring the urgent need for further extensive research in this field.

***Keywords:** Biomedical Waste Management, Artificial Intelligence, Machine Learning, IoT Things, Health Workers, Sustainability.*

Nomenclature:

WHO: World Health Organisation
BMW: Biomedical Waste
IoT: Internet of Things
BMWM: Biomedical Waste Management
HCFs: Health Care Facilities
CPCB: Central Pollution Control Board
CBWMTF: Common Biomedical Waste Management Treatment Facilities

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I. INTRODUCTION

Biomedical waste (BMW), generated from healthcare activities, poses significant risks to human health and the environment. Effective management of BMW is crucial for infection control and environmental protection [1][2]. Traditional methods of BMW management vary across regions and are often influenced by local regulations, resources, and socio-economic factors. These methods typically involve segregation, collection, transportation, and final disposal. However, conventional manual techniques are often inadequate in ensuring safety and environmental protection. The increasing volume of waste produced daily necessitates innovative approaches to address this issue. The use of technology, particularly Artificial Intelligence (AI) and the Internet of Things (IoT), is being explored to enhance waste management processes [3][4].

Sustainable management of biomedical waste has become a growing concern for governments and healthcare facilities worldwide. According to the World Health Organisation (WHO) report, about 75–90% of biomedical waste is non-hazardous, and the remaining 10–25% is hazardous. The amount of Biomedical waste produced and its characteristics depend on many factors, such as the type of health care facility, the specific area within the facility that generates the waste, and patient flow [5]. BMW production in India is estimated at 1.5-2 kg/bed/day [6]. During the COVID-19 pandemic, India generated about 126 tons of BMW per day, accounting for about 18% of the total daily waste. This surge highlights the challenges in managing waste during health crises. Only 15% of BMWs are considered hazardous and infectious. [2,5].

Biomedical waste (BMW), generated from healthcare activities, poses significant risks to human health and the environment. Effective management of BMW is crucial for infection control and environmental protection. The escalating volume of biomedical waste (BMW), coupled with the inherent risks of improper handling and disposal, presents significant challenges to healthcare facilities, environmental agencies, and regulatory bodies. Traditional methods of BMW management vary across regions and are often influenced by local regulations, resources, and socio-economic factors. These methods typically involve segregation, collection, transportation, and final disposal. However, conventional manual techniques are often inadequate in ensuring safety and environmental protection. The use of technology, particularly Artificial Intelligence (AI) and the Internet of Things (IoT), is being explored to enhance waste management processes. This paper reviews the current state of research on AI-enabled smart bin systems, highlighting key technologies, applications, and future directions.

This paper provides a detailed and comprehensive overview of current research and advancements in AI-enabled smart bin systems for biomedical waste management and identifies key areas for future research.

II. SEARCH METHODOLOGY

This review synthesises information from various sources, including peer-reviewed articles, conference papers, systematic reviews, and reports identified through PubMed and Google Scholar. The search terms included “waste management,” “medical waste management,” “smart bins,” “AI,” “machine learning,” and “IoT.” The search was limited to studies published in English, focusing on those providing empirical data or technological frameworks.

III. DEFINITION OF BIOMEDICAL WASTE

The World Health Organisation (WHO) [33] emphasises the importance of proper biomedical waste management to protect human health and the environment. Biomedical waste includes hazardous materials generated from medical laboratories, hospitals, and healthcare facilities. Effective management practices are crucial to minimise risks associated with these wastes.

- Biomedical waste (BMW) includes any waste produced during the diagnosis, treatment, or immunization of humans or animals, as well as during related research activities. It can be solid or liquid and includes infectious or potentially infectious materials. BMW is also known as hospital waste or contagious waste, reflecting the dangerous components it often contains.
- Biomedical waste management (BMWM) is a critical process that involves the safe and sustainable handling of waste generated from healthcare activities [1]**.** The core concept revolves around minimizing the risks associated with this waste, which can pose dangers to human health and the environment. Effective BMW requires a multi-faceted approach that includes proper identification, segregation, handling, transportation, treatment, and disposal of waste [2][4][5].

A. Definition of AI

i. Artificial intelligence refers broadly to computing technologies which resemble processes related to human intelligence, such as reasoning, adaptation and learning, sensory understanding and interaction [7].

ii. Artificial intelligence (AI) is all around us in the twenty-first century. Nearly every sector is using AI, which is advancing rapidly. The term AI, coined in the 1950s, refers to the simulation of human intelligence by machines and encompasses an evolving set of capabilities, including machine learning and deep learning [7].

B. Sources of BMW

The major sources of healthcare waste are hospitals and other healthcare facilities, laboratories and research centres, mortuaries and autopsy centres, animal research and testing laboratories, blood banks and collection services, and nursing homes. High-income countries generate, on average, up to 0.5 kg of hazardous waste per hospital bed per day, while low-income countries generate, on average, 0.2 kg. However, in low-income countries, healthcare waste is often not separated into hazardous and non-hazardous waste, making the actual quantity of hazardous waste much higher.

C. Biomedical Waste Statistics: Global And India

i. Global Biomedical Waste Statistics

Globally, the management of biomedical waste has become increasingly critical, especially in light of the COVID-19 pandemic, which has significantly increased waste volumes. The pandemic has put immense pressure on biomedical waste management systems worldwide, necessitating proper disposal to prevent the spread of infectious diseases [8]. According to WHO/UNICEF, in 2021, only 61% of hospitals had available basic health-care waste services. In the 2023 report, the situation is far worse in fragile environments, with only 25% of healthcare facilities having basic health care waste management services [33].

In a study of medical laboratories in public healthcare facilities, each laboratory generated an average of 4.9 kg of biomedical waste per day. The study highlighted that while many facilities practiced proper waste segregation and treatment, there were deficiencies in transportation and disposal practices [9].

ii. Biomedical Waste Statistics in India

In India, the healthcare sector is rapidly expanding, leading to a substantial increase in the generation of biomedical waste. Currently, India generates approximately 550.9 tons of biomedical waste daily, with projections suggesting this could rise to about 775.5 tons per day by 2022 [10]. The waste generation rate in Indian healthcare units ranges between 0.5 and 2.0 kg per bed per day [12]. A significant portion of this waste, about 75-90%, is non-hazardous, similar to municipal waste, while the remaining 10-25% is hazardous and requires special handling due to its toxic and infectious nature [10] [11].

According to Central Pollution Control Board (CPCB) reports, 764 tonnes of biomedical waste (BMW) (684 Non-COVID BMW+80 COVID BMW) are generated daily, of which 721 tonnes are treated and disposed of in India. There are 3,75,256 Health care facilities (HCFs) in total, of which 1,21,396 are bedded, and 2,53,860 are not. 13,605 HCFs have captive treatment facilities for the treatment and disposal of biomedical waste, whereas 2,62,786 HCFs use the facilities of CBWTFs for biomedical waste collection, treatment, and disposal [36].

In an Indian hospital in Belgaum, the average daily generation of biomedical waste per bed was about 2.31 kg, including both infectious and non-infectious waste. The hospital adhered to regulatory standards for waste segregation, collection, and disposal, primarily through incineration [11]. At SMGS Hospital, Jammu, the average generation of biomedical waste per bed per day was 116.37 grams, focusing only on infectious waste. This figure varied across different wards, with the highest generation in the Gynaecology and Obstetrics department [12].

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IV. OVERVIEW OF COMMON BIOMEDICAL WASTE MANAGEMENT TREATMENT FACILITIES (CBWMTF)

Medical waste management is a critical component of healthcare systems worldwide, with significant variations in practices and challenges across different regions. Effective management is essential to minimise environmental and health risks associated with the improper disposal of medical waste.

D. Global Medical Waste Management Practices

i. According to the National Institute for Occupational Safety and Health (NIOSH), the United States generates 3.5 million tons of medical waste annually. It focuses on handling untreated waste, treating waste, and handling treated waste. It is estimated that more than 10,000 individuals process medical waste, both off-site at commercial treatment facilities and on-site at healthcare facilities [34].

ii. *Common Practices and Challenges:* Many developed nations have established medical waste legislation, but there is often a lack of clarity in defining infectious waste, leading to inefficient sorting and increased disposal costs. Education and standardised sorting are essential for efficient waste management [13].

iii. *Regulatory Frameworks and Challenges:* Globally, there are significant differences in healthcare waste management practices, particularly between low, middle, and high-income countries. Effective regulation and clear definitions of waste categories are crucial for improving national waste management systems. Economic conditions heavily influence treatment and disposal practices, with many countries needing better governance structures and waste segregation practices [14][15].

iv. *Impact of Socioeconomic Factors:* The generation and management of medical waste are influenced by socioeconomic and environmental parameters, such as the Human Development Index and healthcare expenditure. A significant portion of medical waste, approximately 35%, consists of plastic materials, highlighting the need for sustainable resource recovery and recycling [14].

v. *Challenges in Developing Regions:* In regions like Ethiopia, there is a need for improved practices in waste transportation and disposal, despite good practices in segregation and treatment [9].

E. Medical Waste Management in India

i. *Regulatory and Compliance Issues:* In India, the Biomedical Waste Management Rules, 2016, provide a framework for handling and managing biomedical waste. However, compliance varies significantly across healthcare facilities, with many primary health care facilities lacking credible waste management systems. Regular training and improved infrastructure are necessary to enhance compliance and management practices [16] [17] [18].

ii. *Challenges and Risks:* Poor segregation practices can lead to the mixing of biomedical waste with municipal solid waste, posing significant health and environmental risks. Needle stick injuries are a major hazard during waste segregation. There is a need for routine awareness programs and capacity-building to minimise these risks [16] [19].

iii. *Current Practices and Improvements:* Waste generation rates in India range from 0.5 to 2.0 kg per bed per day, with a significant portion of waste being infectious. Many healthcare facilities still dispose of waste alongside municipal solid waste due to inadequate systems and resources. Proposed improvements include better institutional arrangements, appropriate technologies, and staff training programs [17] [2].

iv. Indian hospitals, such as the KLE Society's J. N. Hospital and Medical Research Center, have implemented systems to manage biomedical waste effectively. This includes segregation, collection, transport, storage, and final disposal, often through incineration, in compliance with regulatory standards [11]. Despite these efforts, challenges remain, including inadequate financial resources and insufficient professional training, which hinder effective management of healthcare waste [17]. Training and Compliance: Proper training of personnel and adherence to regulatory guidelines are critical for effective biomedical waste management. This includes the processes of segregation, collection, transport, storage, and disposal [11].

v. *Regulatory Frameworks:* Compliance with national and international waste management rules, such as the Bio-medical Waste (Management and Handling) Rules, is essential for minimizing health risks [11] [12].

V. PROCESS OF BIOMEDICAL WASTE MANAGEMENT PROCESS

Biomedical waste management is crucial for protecting human health and the environment from the hazards posed by infectious and toxic waste generated in healthcare settings. Effective management involves systematic processes to ensure safe handling, treatment, and disposal of biomedical waste.

i. BMW is comprised of various hazardous materials. Categories of BMW include: [1,2,3,4,5]
   - Sharps (needles, scalpels)
   - Infectious materials (blood, body fluids)
   - Pathological waste (tissues, organs)
   - Pharmaceutical waste
   - Chemical waste
   - Radioactive waste
   - General healthcare waste (paper, packaging)

ii. *Source-Based Segregation:* The most fundamental concept of BMWM is segregation of waste at the point of generation. This involves separating different types of waste into colour-coded bins or bags.

iii. *Waste Reduction:* A core principle of BMWM is to minimize the amount of waste generated. This can be achieved through practices such as using fewer disposable items and optimising inventory.

iv. *Safe Handling and Transportation:* BMW needs to be handled and transported in a way that prevents the spread of infection and contamination. This involves using properly sealed and labeled containers and designated vehicles.

v. *Appropriate Treatment:* BMW must be treated using methods that effectively render it safe for disposal. Common treatment methods include incineration, pyrolysis (the devices can function up to 5100°C (9500°F), steam autoclaving (1210°C (2500°F) and a pressure of 15 psi for gravity displacement units), chemical disinfection, and microwave radiation (The internal temperature of the waste is maintained at 950°C (2030°F) [36].

vi. *Environmentally Sound Disposal:* The final disposal of treated BMW should be done in a way that minimizes harm to the environment, often in designated landfills.

vii. *Public Health Protection:* The primary goal of BMWM is to protect public health and the environment from the potential dangers caused by biomedical waste.

A. Importance of BMW

i. *Infection Control:* Proper BMWM is a crucial part of infection control in healthcare facilities. It prevents the spread of infections from contaminated waste.

ii. *Environmental Protection:* It is essential to safeguard the environment by preventing contamination of air, water, and land due to improper waste disposal.

iii. *Legal and Social Responsibility:* Effective BMWM is not only a legal requirement, but also a shared social responsibility. It requires the collaboration of healthcare facilities, government bodies, and professionals.

iv. *Occupational Safety:* Proper BMWM protects healthcare workers and waste handlers from potential injuries and infections caused by handling hazardous waste.

v. *Health and Environmental Safety:* Inappropriate management of biomedical waste can lead to infections among healthcare workers, patients, and the community, and can cause environmental pollution [2] [16].

vi. *Regulatory Compliance:* Countries like India have established comprehensive rules to ensure biomedical waste is managed without adverse effects on human and environmental health [2] [16].

vii. *Public Awareness and Training:* Proper training and awareness programs are essential to minimize health risks and ensure compliance with waste management protocols [16]. Proper waste management protects the community by minimizing the risk of infections, air and water pollution, and contamination.

B. Biomedical Waste Management Processes: Proper BMW Management Involves Several Key Steps

i. *Segregation:* Waste must be sorted at the point of generation into categories based on its type (e.g., solid, liquid, biodegradable, non-biodegradable, general, pathological, radioactive, and infectious waste) at the source of generation. Segregation at the source is crucial for effective BMWM. A major challenge in healthcare waste management is the lack of proper segregation and disposal practices, especially in developing countries. This can lead to mixing hazardous and non-hazardous waste, increasing the risk of infection and environmental contamination [10,15,24].

ii. *Collection:* Waste needs to be collected and handled properly using specific guidelines. Biomedical waste should be collected in designated containers and stored safely to prevent exposure and contamination [8].

iii. *Transportation:* Waste needs to be transported safely using appropriate methods to prevent contamination. Safe transportation protocols are necessary to move waste from healthcare facilities to treatment sites without risk of spillage or exposure [2].

iv. *Treatment:* Various treatment methods exist, such as autoclaving, incineration, thermal inactivation, chemical disinfection and landfilling [35,36,20].

v. *Disposal:* Recycling, landfills, and incineration are common disposal techniques. The CBMWTF consists of secure land disposal facilities, an incinerator, a shredder, and an autoclave. In Tamil Nadu, there are eleven CBMWTFs in operation. The type of garbage and local laws determine which approach is best. However, each approach has its pros and cons [3] [20].

C. Methods of Segregation

i. Colour-coded bins and bags are used to segregate different categories of waste. The colour acts as a visual aid for healthcare workers to dispose of different types of waste correctly.

- Yellow bins are typically used for human and animal anatomical, soiled waste, infectious, chemical, laboratory, and pharmaceutical waste.
- Red bins are used for recyclable contaminated wastes.
- Blue containers are for glass waste, metallic body implants, screws, nails, plates,
- White bins are for sharp objects, including metal waste.

ii. Manual segregation is a common method used in many healthcare facilities, were workers manually separate waste into different categories.

iii. Automated systems using AI-powered image recognition and machine learning algorithms are emerging to identify and sort biomedical waste. These systems aim to minimize human error and expedite the segregation process.

iv. Some studies explore the use of humidity sensors in waste bins to distinguish between wet and dry waste.

v. Image processing techniques are also being proposed to segregate medical waste, which helps in identifying and categorizing the waste.

D. Impact of Improper Segregation and Treatment Facility

i. Improper segregation and

disposal of BMW directly impact human health by spreading infections through microbial hazards. Mismanagement of BMW can lead to community health problems, increasing the risk of infections, air and water pollution, and contamination of animals and scavengers. The inappropriate disposal of sharps can cause injuries and infections to handlers. Inappropriate segregation can also hinder the ability to recycle certain materials, harming the environment.

ii. An estimated 16 billion injections are given annually throughout the world. Not all syringes and needles are properly disposed of, increasing the risk of infection, harm, and reuse. In low and middle - income countries in recent years, due to the advancement of treatment facilities, the injection with contaminated needles and syringes has significantly reduced. In the 2010 report, despite these advancements, approximately 33,800 new HIV infections, 1.7 million hepatitis B infections, and 315,000 hepatitis C infections were still caused by unsafe injections[33, 35].

iii. High Rates of Inadequate Systems: A study across 20 states in India found that 82% of primary health centres and more than 50% of secondary and tertiary care facilities had inadequate BMWM systems. This highlights a widespread problem in the infrastructure for proper waste handling [5]. The perception is that human error and lack of experience are major causes of segregation problems. This suggests that even when systems are in place, they are not always followed correctly. In one survey, when healthcare workers were asked to rate their agreement with the statement "There is trouble in identifying the right bin to dispose of the waste in", there was clustering of responses, suggesting the facilities do face problems with waste segregation.

iv. The study from Ethiopia indicates that many private healthcare facilities lack proper waste segregation practices, storing, transporting, and disposing of waste incorrectly. This study showed that more than half (52.3%) of healthcare workers disagreed that HCWs should be segregated at the point of waste generation. This study found that, despite a majority of respondents agreeing that improper colour coding increases the risk of injury, only 47.7% agreed that HCW should be segregated at the point of waste generation [21]. Inaccurate categorisation of municipal waste is considered dangerous, affecting the health of people and animals and impeding plant development, underscoring the need for accurate waste classification.

E. Improper Transportation

i. A study found that waste bags were not cleared on time, uncovered trolleys were in use, and sharp containers were improperly closed during transportation within healthcare facilities. This demonstrates a lack of adherence to safe transportation protocols. Waste is transported along designated routes, but the location of lorries is not consistently tracked [5]. During medical waste collection, multiple copies of documents are exchanged among hospitals, storage facilities, transportation contractors, and disposal stations for each waste consignment, which may lead to loss or inaccuracy [5]. (5) A study in Ethiopia revealed that 21.2% of the private clinics do not have separate HCW transportation to the disposal site, and the same study showed that 22% of private clinics do not close HCW containers during transport [21].

ii. Artificial intelligence can enhance multiple facets of waste management in smart cities, such as logistics, sorting, and resource recovery. Using AI in waste logistics, transportation distances can be reduced by up to 36.8%, costs by up to 13.35%, and time by up to 28.22%. AI also enables waste identification and sorting, with accuracy rates ranging from 72.8% to 99.95%. When combined with chemical analysis, AI further improves waste pyrolysis, carbon-emission estimation, and energy-conversion processes [22].

iii. A key application of AI in biomedical waste management is route optimisation, which entails designing the most efficient pathways for transporting the energy waste from healthcare facilities to disposal sites. By accounting for this approach, transportation risks are reduced, and a healthier environment is promoted [23].

F. Improper Disposal

i. *Storage Issues:* Many small healthcare facilities store BMW for up to 3 days, despite regulations requiring storage for a maximum of 2 days. Only 1.4% of small facilities have everyday collection. Small HCFs face more space constraints and longer storage times due to infrequent collection by CBWTFs. Many studies do not examine the type and condition of processes and treatments recommended by the WHO, which are critical for safe disposal. In the United States, up to 85% of hospital waste does not require infectious waste treatment, indicating a potential over-treatment of general waste due to poor segregation [6].

ii. *Open Dumping:* Improper disposal of BMW, including open dumping, can cause severe air, water, and land pollution, which can lead to health risks for both humans and animals [2]. Globally, one in three healthcare facilities does not safely manage HCW. Safe waste management services are often lacking, particularly in low-income countries [21].

These statistics and findings underscore significant gaps in the proper management of biomedical waste. Issues with segregation, transportation, and disposal methods increase risks to healthcare workers, the public, and the environment. The sources highlight the need for better training, infrastructure, and more effective regulation to ensure BMWM practices are effective.

VI. AI – DRIVEN BIOMEDICAL WASTE MANAGEMENT

Artificial Intelligence is more than just a technological advancement; it is becoming an integral part of human society, significantly impacting our present and likely playing an even greater role in the future. Following the pandemic, there has been a notable shift towards technology use, particularly in education, where AI has transformed teaching and learning methods. It offers numerous applications for students, educators, and everyone involved in the educational sector. AI offers opportunities to cater to diverse learning styles and address essential educational needs.

i. *Concept:* The overarching concept is to move from traditional, often inefficient, manual waste management to a more digitized, automated, and sustainable approach. This involves:

ii. *Utilizing Technology:* Employing AI, IoT, and machine learning to enhance waste segregation, collection, transportation, and disposal.

iii. *Real-Time Monitoring:* Using various sensors such as near-infrared (NIR), X-ray transmission, and optical sensors, to detect and classify materials based on their physical properties, such as colour, size, composition density and digital surveillance tools to monitor waste status in real-time, allowing for timely interventions [37,38].

iv. *Data-Driven Decisions:* Using data collected from waste management processes to make informed decisions about resource allocation and waste reduction strategies.

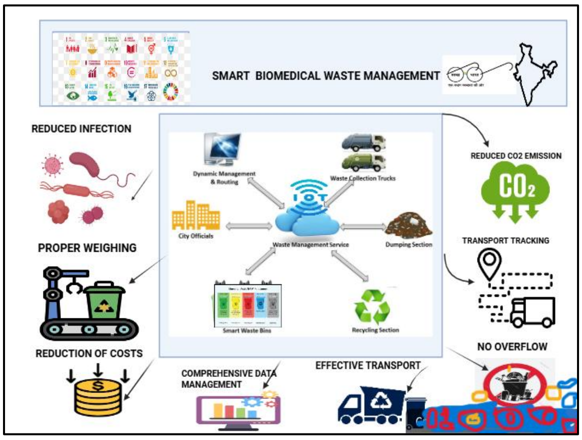
v. *Standardization:* Developing standardized protocols for waste audits and reporting to ensure comparability and facilitate better waste management practices.

vi. *The 5Rs Rule:* Employing the 5Rs rule (reduce, reuse, recycle, rethink and research) as a common strategy to derive maximum practical benefit from resources while generating a minimum of waste.

A. Application of Various Technologies in AI-Enabled Smart Bin Systems

Innovations in biomedical waste management are crucial for addressing the increasing volume and complexity of waste generated by healthcare facilities. Recent advancements focus on integrating technology to enhance efficiency and safety in waste management processes. The reviewed literature highlights the application of various technologies in AI-enabled smart bin systems:

i. ***Internet of Things (IoT):*** It provides connectivity between devices for data collection and exchange, essential for real-time monitoring of waste bins. IoT technologies are being used to monitor medical waste in real time, improving the efficiency of waste management processes. Sensors in waste bins enable digital surveillance, providing timely updates and enabling better management of waste storage, transportation, and disposal [4].



[Fig.1: AI-Driven Smart Waste Management (From Waste to Energy)]

ii. *Artificial Intelligence (AI):* AI, including machine learning and deep learning models, is being applied to optimise the collection, segregation, transportation, and disposal of biomedical waste. These technologies enhance resource allocation, risk mitigation, and decision-making processes [2].

iii. *Machine Learning (ML):* Algorithms analyze data to predict patterns and optimize waste management processes. Techniques such as Support Vector Machines (SVMs) are used to predict waste quantities [37,38].

iv. *Deep Learning (DL):* A subset of ML, utilizing Convolutional Neural Networks (CNNs) for complex tasks such as image recognition and waste classification [3, 38, 37,38].

v. *Genetic Algorithms (GA):* Used for optimizing routes for waste collection and estimating waste generation [37, 38].

vi. *Robotics**:*** To reduce human contact with hazardous materials, some sophisticated systems incorporate robotic arms for automated garbage processing and sorting. Robots can handle a variety of waste materials with varying sizes, shapes, and textures. Grippers with touch sensors and movable grabbing mechanisms. To improve safety and efficiency in recycling operations, collaborative robots, or cobots, are being used to operate alongside human operators. Utilising automation and robotics in waste recycling enhances total resource recovery rates, boosts throughput, lowers labour costs, and streamlines operations [39, 40, 41].

vii. *Blockchain**:*** Provides a transparent, secure, and traceable record of waste management, enhancing accountability and compliance.

viii. *RFID Tags**:*** Enable tracking of waste from the point of origin to disposal, which is crucial for secure disposal of biohazardous materials.

ix. *Nanophotocatalysts:* These materials are gaining attention for their ability to degrade pollutants in biomedical waste. They offer a green, eco-friendly solution due to their non-toxicity, low cost, and high absorption fficiency, making them suitable for photodegradation processes [25].

x. *Integrated Low Heat Treatment Systems*: Techniques such as autoclaving, microwaving, and solar systems are being developed to reduce the environmental impact and transportation costs associated with waste treatment. These methods aim to minimise infection risks and reliance on less environmentally friendly techniques such as incineration [26].

xi. *Automated Waste Segregation:* Innovations include the development of instruments that automate waste segregation using colour-coded systems, reducing human exposure and improving the efficiency of waste handling and disposal [27].

B. Benefits of AI in Biomedical Waste Management

i. *Reduced Infection Risk:* Healthcare waste contains potentially harmful microorganisms that can spread among healthcare personnel, leading to serious illnesses. The most common procedures posing high risks include injections and handling of sharps, which can lead to infections such as HIV, hepatitis B and C, tuberculosis, and more if not properly managed [28]. IoT sensors can prevent waste bin overflow, and machine learning can identify infectious waste. Robots can also safely manage waste, and blockchain can ensure secure tracking of disposal.

ii. *Cost Reduction:* IoT technology can reduce fuel and labour costs in waste collection. Machine learning optimises resource allocation and deep learning automates waste sorting, thereby reducing costs. Blockchain streamlines administrative tasks, further reducing costs.

iii. *Enhanced Efficiency:* AI-assisted methods expedite the segregation process, minimise human error, and improve waste collection and disposal.

iv. *Improved Sustainability:* By optimizing waste management processes, AI contributes to more sustainable and environmentally conscious practices. The use of AI and IoT can lead to better resource allocation and waste-to-energy technologies.

C. Challenges and Identified Gaps

i. While most studies focus on bin status and condition, there is a need for research encompassing the entire waste management process, including segregation, storage time, transportation routes, and treatment. More research is needed on the digitalization of medical waste management. There is limited literature specifically addressing digitalization in medical waste management [4]. There is a need to develop environmentally friendly methods and protocols for BMW disposal [2].

ii. Traditional methods of biomedical waste management have several limitations, including a lack of infrastructure, inadequate training, and environmental and health risks.

D. The Identified Gaps Are

i. *Manual Processes:* The reliance on manual segregation, collection, and disposal methods leads to inefficiencies and inaccuracies. Human error can result in improper waste handling, posing health risks to workers and the public.

ii. *Insufficient Monitoring:* There is often a lack of real-time monitoring and tracking of waste generation, segregation, and disposal. This makes it challenging to identify and address issues promptly.

iii. *Inadequate Integration of Technology:* Technology awareness and its use in biomedical waste collection to treatment is not much emphasize.

iv. *Lack of Education & Training:* Limited focus on healthcare workers' education and training in waste management, leading to increased post-collection segregation process and handling affecting health, time and cost.

v. *Limited Optimization:* Current systems lack real-time analytics and optimization capabilities to streamline waste management processes. This can lead to increased costs, resource wastage, and environmental impact.

vi. *Health and Safety Concerns:* Manual handling of biomedical waste increases the risk of exposure to infectious materials, posing health hazards to healthcare workers and the community.

vii. *Environmental Impact:* Inefficient waste management practices contribute to environmental pollution and contamination, affecting ecosystems and public health.

viii. *Scalability Challenges:* With the increasing volume of biomedical waste generated daily, traditional methods may struggle to scale efficiently to meet demand, leading to bottlenecks and delays.

VII. FUTURE DIRECTIONS AND RECOMMENDATIONS

Future research should focus on addressing the limitations identified in the current literature:

i. *Holistic Systems:* Development of systems that monitor the entire waste management process, from generation to disposal, rather than just focusing on bins.

ii. *Comprehensive Datasets:* Creation of more comprehensive and diverse datasets to improve the accuracy and reliability of machine learning algorithms in waste classification.

iii. *Cost-Effectiveness Analyses:* Thorough assessment of the cost-effectiveness of different AI-driven waste management technologies to ensure economic feasibility.

iv. *Standardized Reporting:* Implementation of standardized reporting methods for waste audit studies to improve comparability and replicability across different settings.

v. *Integration of Technologies:* More attention should be given to integrating blockchain technology to improve the transparency and security of waste disposal.

vi. *Exploration of AI in Waste Prediction:* Expansion of AI's capacity to predict waste generation patterns to improve waste management strategies.

vii. *Sustainable Management Models:* The integration of sustainable waste management models, such as the Global Waste Management Outlook framework, can be adapted to meet country-specific needs. The use of digital tools, like GIS-integrated real-time waste management systems, can enhance monitoring and compliance [32].

viii. *Training and Awareness:* Continuous training and awareness programs for healthcare workers are crucial to improving waste management practices. Understanding the importance of proper waste segregation and disposal can significantly reduce environmental pollution and health risks [31, 32].

ix. Despite the promising potential of AI in BWM for comprehensive approaches that combine technology with traditional methods, challenges remain. Hence, further research is an avenue for overcoming these challenges to realise a better version of AI in this area [29, 30].

VIII. CONCLUSION

The integration of advanced technologies such as AI, IoT, robotics, and blockchain in biomedical waste management represents a transformative step toward improving efficiency, safety, and sustainability in healthcare waste practices. Smart systems equipped with sensors and automated features enable enhanced segregation, monitoring, and disposal, reducing risks and environmental impact. Innovations like nanophotocatalysts and integrated treatment systems further contribute to eco-friendly solutions. Addressing these challenges requires a comprehensive approach that includes improved regulatory compliance, infrastructure development, and widespread education and training. Effective biomedical waste management is critical to protecting healthcare workers, communities, and the environment from the risks associated with improper waste handling. From Waste to Smart Transformations, AI-driven biomedical waste management has become a critical necessity at the global and regional levels, underscoring the urgent need for further extensive research in this field. By fostering collaboration between policymakers, healthcare providers, and technology developers, the global community can build safer, more sustainable biomedical waste management systems that mitigate health and environmental risks.

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As the article's author, I must verify the accuracy of the following information after aggregating input from all authors.

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