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REVIEW ARTICLE

Modernized Management of Biomedical Waste Assisted with Artificial Intelligence

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Abstract

Biomedical waste can lead to severe environmental pollution and pose public health risks if not properly handled or disposed of. The efficient management of biomedical waste poses a significant challenge to healthcare facilities, environmental agencies, and regulatory bodies. Traditional management methods often fall short of efficient handling of biomedical waste due to its enormous quantity, diverse, and complex nature. In recent years, different approaches employing Artificial Intelligence (AI) techniques have been introduced and have shown promising potential in biomedical waste management. Wireless detection and IoT methods have enabled the monitoring of waste bins, predictions for the amount of waste, and optimization of the performance of waste processing facilities. This review paper aims to explore the application of AI through machine learning and deep learning models in optimizing the collection, segregation, transportation, disposal, and monitoring processes, which leads to improved resource allocation with risk mitigation of biomedical waste along with prediction, and decision-making using AI algorithms.

Key Words: *AI in waste management; IoT in waste management; Blockchain technology; Biomedical waste segregation; Robotics in BMW*

Abbreviations: AI: Artificial Intelligence; BMW/BMWM: Biomedical Waste Management; CPCB, India: Central Pollution Control Board, India; CBWTF/CBMWTF: Common Bio-medical Waste Treatment Facility; OSHA: Occupational Safety and Health Administration; WHO: World Health Organization; EU: European Union; GIS: Geographical Information System; MWM: Medical waste management; IoT: Internet of things; RFID: Radio Frequency Identification; POI: Point of Interest; MLDPAF: Machine Learning-driven Predictive Analytic Framework; DPoS: Delegated Proof of Stake; RTOS: Real Time Operating System; DL: Deep Learning; GA: Genetic Algorithms; CNN: Convolutional Neural Networks; LSTM: Long Short-Term Memory; CI: Cohort Intelligence; IBW: Infectious Biomedical Waste; IMW: Infectious Medical Waste; SCND: Supply Chain Network Design

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Introduction

The status quo of Biomedical Waste Management (BMW) is gigantic and needs to be addressed in a global scenario. Nowadays, individuals are highly conscious about their health, so cognizant measures are usually taken by them for monitoring health and infections, which has alleviated the generation of bio-medical waste. Rapid growth in health care, rise in hospitalizations, clinical visits, and laboratory diagnosis has also increased multi-fold in the post-COVID-19 pandemic era which is directly correlated with the generation of BMW. Traditionally, biomedical waste management has relied on manual categorization, handling, and disposal, which can be error-prone, time-consuming, and pose serious health risks [1]. The conventional and manual methods of BMW have loopholes, face challenges, need to be rectified, and more consistent. Although Artificial Intelligence (AI) has versatile applications in different realms associated with health and the environment, however, the integration of AI technologies is at the pristine stage in BMW. AI holds profound promise in revolutionizing the entire process, from waste collection to disposal, with enhanced efficiency and precision. The emergence of AI has addressed these challenges by introducing automated systems that can accurately identify, sort, and manage biomedical waste, ensuring optimal safety and environmental compliance. AI-powered image recognition and machine learning algorithms can automate the categorization of different types of biomedical waste, such as sharps, infectious materials, and hazardous substances [2]. AI-assisted methods would not only expedite the segregation process but will also minimize the potential for human error. The predictive analytics of AI assists in forecasting of waste generation patterns and optimization of waste collection routes. Thus, the operational costs could be reduced, the disposal procedures would be streamlined, and manual handling would be reduced [3]. The advent of AI in biomedical waste management (BMW) signifies a paradigm shift, surmounting traditional limitations through automated sorting, accurate categorization, and data-driven decision-making. This paper delves into the trans-formative influence of AI on biomedical waste management, exploring the multifaceted benefits it brings to the table. As the AI technology leap holds the potential to significantly enhance safety, efficiency, and sustainability across the entire biomedical waste management BMW spectrum; hence the present endeavor is to raise awareness among the professionals and policy makers in this regard.

Conventional Methods of BMW Treatment

Over the years different regions around the world have adopted varying approaches to BMW biomedical waste management, often influenced by local regulations, infrastructure, resources, and socio-economic factors. As per the guidelines issued by government organizations such as the Central Pollution Control Board (CPCB, India) and Ministry of Environment, Forest & Climate Change (India), the management of biomedical waste has to be carried out in the following steps:

- The segregation of waste in color-coded and barcode-labeled bags/containers, is to be carried out at the source of generation.
- Pre-treatment of the laboratory and highly infectious waste
- Transportation of segregated waste to a central storage area within the setup.
- Temporary storage of biomedical waste in the central storage area
- Picking and transporting biomedical waste for treatment to Common Bio-medical Waste Treatment Facility (CBWTF).

- Final treatment and disposal of biomedical waste at CBWTF [4].

Some traditional methods of biomedical waste management are:

1. **Incineration:** The bio-medical waste is exposed to high temperatures in specially designed incinerators. This method helps in the complete destruction of infectious agents, reducing the waste to ashes and gases [5]. However, it can release pollutants into the air and requires careful monitoring to ensure proper combustion and minimal environmental impact.

2. **Autoclaving:** It is the process that uses steam and high pressure to sterilize biomedical waste, killing pathogens and rendering the waste safe for disposal. The treated waste can then be sent to regular landfills. Though quite effective, the method consumes energy and requires proper equipment and trained personnel to operate safely [6].

3. **Chemical disinfection:** It involves using disinfectants or chemicals to treat biomedical waste, to reduce its infectivity. Bleaching powder and other strong disinfectants are used for this purpose. The treated waste is then often disposed of in landfills or other waste management facilities [7].

4. **Microwave radiation and nano photocatalysis:** It utilizes microwave radiation and nano photocatalysts, an emerging and novel technique, for managing hazardous biomedical waste containing radioactive elements. This waste treatment approach can be applied in both stationary facilities and through mobile units integrated into treatment vehicles [8].

5. **Mechanical treatment:** It involves shredding or grinding biomedical waste to reduce its volume, followed by disinfection using heat or microwave technology. While these methods can be effective in reducing waste volume, they may not eliminate all pathogens [9]. In some regions, burial of biomedical waste is practiced, where waste is buried in designated areas with specific precautions. However, this method has the potential to contaminate soil and groundwater if not properly managed.

6. **Land-filling:** Non-infectious biomedical waste that has been appropriately processed may be able to be disposed of in standard landfills. However, the risk of unintentional exposure is mitigated with careful storage and labeling. The biomedical waste containing sharp-edged items and other materials designated for are safely placed within deep trenches. Lime is applied to these items, inserted in the trenches; then subsequently filled with soil to ensure proper containment and disposal [10,11].

Challenges Faced by Conventional Methods of Biomedical Waste Disposal

Traditional methods of biomedical waste management have faced several challenges, like many healthcare facilities, especially in low-resource settings, lack of proper infrastructure for the safe collection, storage, and treatment of biomedical waste. Often found that healthcare workers and waste handlers are not adequately trained in proper waste management procedures, leading to potential exposure to hazardous materials and increased risk of infections [12].

The healthcare industry’s growth and increased medical waste generation have put pressure on existing waste management systems, potentially leading to overload and inadequate waste handling [13]. Pandemics like COVID have strained existing biomedical waste management systems, leading to challenges in the safe disposal of large volumes of infectious waste. High working temperatures of incinerators and steam sterilizers, as well as harmful chemicals released into the atmosphere following waste treatment, are also linked to physical and health risks. The environmental effects of incorrectly operating incinerators or other medical waste treatment equipment as well as the visual damage to the environment brought on by irresponsible disposal are among the public repercussions. A shift in the microbial ecology and the spread of antibiotic resistance can result from improper waste management [14]. The faulty practices of mixing of non-hazardous waste to BMW is also problematic and necessitates the segregation of BMW at source only. Improper disposal could release infectious hazards in the environment and also encourage the recycling of prohibited disposables [15].

In developed countries for instance a city hospital in Florida, United States the biomedical waste generation rate is as high as 10.7 kg/bed/day. Whereas the upper and lower-middle-income countries, (e.g., hospital at Shiraz, Iran) higher BMWGR of 14.8 kg/bed/day has been reported [16]. COVID-19 pandemic waves have led to an enormous increase in BMW production [17]. In the Hubei Province (China), BMWR was 0.5 kg/bed/day due to COVID-19 and the net increase of medical waste volume was about 3366.99 tons during the first pandemic wave only [18]. In India, there was an incremental generation of COVID-19 BMW, an amount of 84.61 TPD of COVID-19 BMW was generated between May 2020 to February 2022, from different healthcare concerns [19].

Current Guidelines for BMW Management

To solve the dilemma of BMW, public health organizations and authorities have enforced measures and guidelines for the safe disposal of BMW across the globe. World Health Organization issues guidelines on the Safe management of waste from healthcare activities in the WHO Blue Book; the document which highlights the key aspects of safe healthcare waste management, and guides policymakers, practitioners, and facility managers worldwide [20]. The organizations such WHO, U.S. Occupational Safety and Health Administration (OSHA), European Union (EU), Central Pollution Control Board (CPCB) of India, have amended the policies to ensure public safety [21]. Moreover, the government of various countries amends the BMW rules regularly, previously notified in 2016 by the Ministry of Environment, Forest and Climate Change, India in a gazette [4].

During the COVID-19 pandemic in India, Central Pollution Control Board (CPCB), directed the designated nodal officers of the quarantine/isolation center to get registered on CPCB's biomedical waste Tracking App 'COVID19BWM' (available on Google play store) and to update the details of waste generated on daily basis [19,22,23]. Further, Common Biomedical Waste Treatment Facility (CBWTF) operator was also instructed to register at the app and should ensure the registration of Waste Handler (with vehicle) for entering the data of COVID-19 biomedical waste received and disposed [24]. Recent Mobile Applications recommended by the government such as 'COVID19BMW' allow the mapping of BMW data by Geographical Information System (GIS) which could provide a synoptic view throughout the country and could identify the BMW threat areas [23].

Conventional Data Sampling for Biomedical Waste

The conventional data analysis and interpretation approaches were analogously followed by traditional segregation, treatment, and disposal methods. For example, a cross-sectional study was conducted in medical and dental clinics, specialized medical, laboratory clinics, polyclinics, and midwifery clinics in Phuket, Thailand to assess the ongoing medical waste management. Stratified-random sampling was done to select the sample of 344 respondents from 172 clinics; a questionnaire was designed to collect the data using face-to-face interviews. Four aspects of medical waste: segregation, collection, transportation, and final disposal and questions elicited the information about the respondents' KAP (K-Knowledge of MWM, A-Attitude towards MWM, P- Practice in respect of MWM). KAP scores were determined and analyzed as low, medium, and high levels. Respondents with longer working experience showed better practical and management skills with respect to MWM as compared with those with less working experience [25]. Though the study was interpretative, automated data handling and analysis would be more relevant in the present context.

IoT & Machine Learning in Biomedical Waste Management

Applying Internet of things (IoT), waste collecting & segregating devices can be interrelated to connect and exchange data (using data access networks) with other IoT devices and the cloud. The devices are typically embedded with technology such as sensors and software, and can include mechanical, digital machines and sometimes also consumables (waste-bags/medical devices). Trash bins are recent IoT devices, equipped with ultrasonic or gas sensors, which determine the level of waste. Sensors manage lid opening and closing through servo motors, while a camera module aids in waste management and color-based classification. When the bin gets filled or emits a foul odour, which is detected by sensors), a buzzer is emitted. The garbage is maintained using Arduino and wireless fidelity, information gets transmitted to the cloud network, SMS alerts can be received by frontline workers, shippers and officials at CBMWTF for further [26,27]. A study in the Kaduna area, (Nigeria) explored the use of Internet of Things (IoT) solutions to enhance healthcare waste management. IoT sensors triggered alarms and messages for waste collection, revealing a positive correlation between bed quantity of hospitals and daily waste generation. The variation in the types and quantities of hazardous waste produced by different hospitals, underscores the need for specialized waste management. The research underscores the effectiveness of IoT technologies in improving biomedical waste management, with smart bins reducing response times. Biomedical waste constitutes a significant portion of hospital solid waste. This technology holds promise for healthcare waste management in Nigeria. A correlation matrix was subjected to Principal Component Analysis, revealing eight distinct components. Notably, the first component (associated with the National Eye Centre) explained a significant proportion of the variance in waste sources derived from the initial variables. In contrast, the second component (linked to Yusuf Dantsoho Memorial Hospital) accounted for a smaller portion of the original variance, while the remaining components made negligible contributions in summarizing the variations in the sources of solid waste. In summary, the study suggests prioritizing specialized waste management for chemical, radiology, pathology, pharmaceutical, infectious, and highly infectious waste, while simpler methods suffice for other sources, like burning or industrial recycling with minimal training [28]. According to the 'raspberry model - ultrasonic sensors' interfaced system connects the dustbins to the internet so as to acquire the real-time information about the dustbins. The ultrasonic sensor detects the waste-level in the bin, and signals are conveyed to raspberry pi, which are then encoded and further sent to the application. The data gets received, analyzed and processed in the database using 'Python' and 'Scratch' as a programming languages; further sent over to cloud e.g., Node-RED. The concerned authority receives the alert about the amount of waste in the dustbin, when gets full the concerned person can be directed for the collection from the particular area [29] (Figures 1A and 1B).

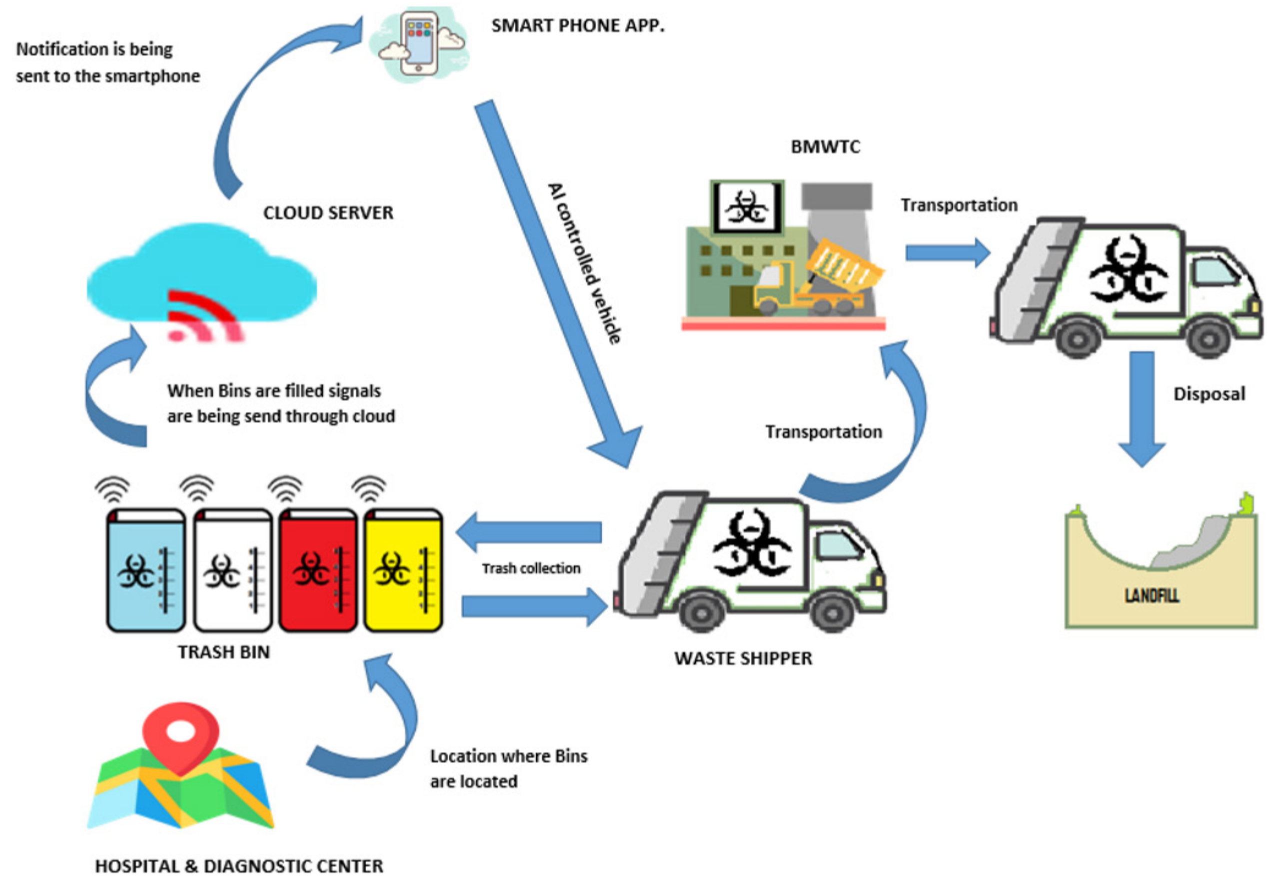

Figure 1A) *Artificial intelligence assists in waste segregation, collection, transport, and disposal of biomedical waste from a hospital/diagnostic center to biomedical waste treatment center.*

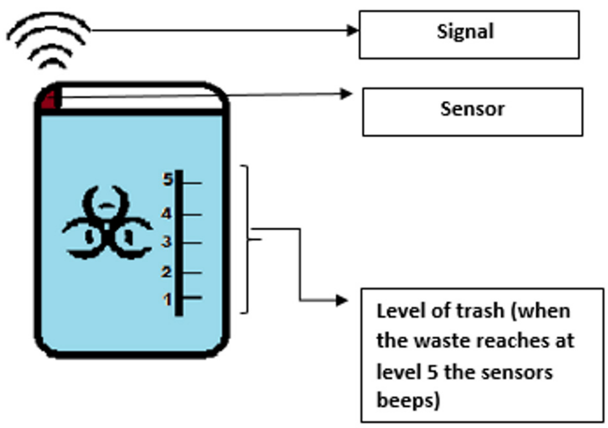

Figure 1B) *Trash bins equipped with sensors, buzzes a signal at a level (fill/about to fill) and emit a signal.*

Radio Frequency Identification (RFID) tags, specific tags assigned to specific garbage bins; have also been in use for medical waste and enables the measurement and tracking of waste disposal. Based on the tag information (obtained by a chain-way mobile operator/ handheld device/scanner device), different type of waste material is dropped in pre-decided beans. RFID technology could monitor manage/track the transport of waste from the source to the shipper and finally to the disposal center; the black marketing of medical waste can also be monitored. Any violations can be easily captured, detected, and prosecuted [30]. Based on based4G/5G modules, Bluetooth positioning technology consists of iBeacon Bluetooth, Bluetooth positioning terminal, LoRa communication base station, positioning and map engine, deployment inspection + POI information management and calibration App, mobile app, server software, has been used in hospitals in China. The vehicles involved in waste collection and transfer equipped with a Bluetooth positioning terminal tag, are continuously monitored and visualized [31].

Neural networks can be used to estimate the waste volume and an improved machine learning algorithm to improve waste collection;

'Energy and Waste Management Machine Learning-driven Predictive Analytic Framework (MLDPAF)'; reduces the waste amount, landfill analysis, and transportation by 90%, 40%, and 15%, respectively [32].

Blockchain Technology in Biomedical Waste Management

Blockchain, a groundbreaking technology; that started with cryptocurrencies, now can also applied to BMW. In order to properly manage, coordinate and monitor the wastewater and medical waste, a system based on blockchain technology and the Internet of Things (IoT) is futuristically devised. In the realm of hospital waste management, IoT-enabled containers gauge waste quantities, and track, and exchange data among entities. These insights are relayed to a Blockchain via WiFi, 4G, or 5G, for real-time processing within set intervals. Data blocks are aggregated and validated using DPoS, a consensus algorithm, pioneered by Daniel Larimer in 2014 [33]. In order to encourage sustainability in BMW, the organizations employing reduction and recycling practices are rewarded through the issue of blockchain-based tokens, which can be exchanged in the form of some benefits or funding [34].

The upsurge in BMW during the pandemic waves of COVID-19 has also been managed through block-chains. The specific algorithm was developed to define the interactive rules of Ethereum blockchain with COVID waste management. As and when the medical waste from a COVID testing/treatment facility gets shipped to the waste treatment facility (usually via third-party shipping services) for treatment and disposal; a registered user/system gets represented by a unique Ethereum address; can also be mentioned as that a call is generated. RFID tags are installed on the waste package, which are registered, recorded, and designated a unique Ethereum address on the blockchain. As the waste gets picked the COVID-19 status of the deployed person (waste handler/shipper) gets notified. Compliance with COVID-19 standard operating procedures has to be checked; staff and shippers having COVID-19 symptoms were not allowed to handle medical waste. However, permission was given to those who have received COVID-19 vaccination. At the time of shipment and throughout the transit period, the integrity of the seals and tags on the bags has to be assured. The smart contract which corresponds to the unique ID of the waste bag keeps the user as well as the waste treatment facility informed about the data and state of the medical waste during its shipment. The authority can cancel the license of the shipper if the COVID-19 medical waste if there has been any mishandling of waste During the traditional process of biomedical waste collection and treatment the documents were used to exchanged six times manually between different personnel, which could result in errors, malpractices, and transmission of infections. The digitalization of documentation and tracking processes would significantly reduce these problems [35]. Recerreum is a blockchain platform, employs smart contracts to incentivize waste segregation. RFID-tagged waste bins with sensors measures the waste quantity and uploads data to the blockchain. Users scan the tags to create accounts and, when segregating waste, receive rewards calculated by smart contracts. The platform automates transactions, transferring rewards to users' bank accounts [36].

Robotics in Biomedical Waste Management

Conceiving the idea of non-human intervention in BMW, a robot design has been proposed with a camera and controlled motion; can segregate the medical wastes under the guidance of the operator. The multitasking robots are able to sort tons of garbage in a single day; in the colour-coded bins [37]. A camera and individual Arduino controls (microprocessors) are embedded in the body of the robot. The configuration also includes robotic cars, a blender, and an arm (for sterilization) and a microwave. The robotic camera enables to view the periphery so as to monitor its motion, which is controlled using the software. One robotic arm is meant for picking, placing, and segregating the waste while other carried out the sterilization externally. After the segregation, robot engulfs the general and metallic waste, heat treatment kills the microorganisms. The metallic waste gets ejected out using the metal pulling mechanism and general waste (paper, plastic and cotton) gets engulfed, sterilized and recycled. The cost of the proposed robot is estimated to be around 7000 to 8000 in Indian rupees currency, the maintenance cost could be 2000 to 3000 rupees. Compared to the conventional methods it seems to be cost effective but requires continuous monitoring and lacks decision-making ability. Further, additional features such as decision-making algorithms, Bluetooth signals, GPS mapping feature with a camera, and a height manager can be incorporated [38].

Real time systems and 'Arduino' embedded with microcontroller have also been employed in the robotic transport of trash from the smart bins to the disposal site can be carried out by RTOS methodology. As the smart bins get filled with trash, and reaches the upper edge, the 'Arduino' based microcontroller sensors send the message to the robot for waste collection through CC2500 RF module. Receiving the message from the server, the mobile robots navigate, move safely in a human-populated environment, and collect the waste [39].

Deep Learning and Neural Networks in Segregation and Treatment of Biomedical Waste

Deep Learning (DL) has gained prominence in addressing various solid waste management issues through diverse computational approaches. Researchers are actively engaged, leading to substantial recent research, notably over the last decade. Deep Convolutional Neural Networks and waste-sorting robots are being employed in landfills, capitalizing on their computational requirements and sorting capabilities [40]. Genetic algorithms also offer an intelligent solution for waste management; (GA)–fuzzy inference engine based upon Mamdani model has been employed for waste estimations. Fuzzy inference uses small-size sensors which are also cost-effective, determines and senses the probability when the smart bin is about to be full. Segregation of waste based on recycling is an additional feature of has also been of GA-FIS, collection priorities and disposal strategies can also be performed; hence can also be applicable to BMW. Route optimization, pick-up schedule and resource allocation can improve the BMW strategies [41]. A study signifies effective medical waste management; relies on accurate forecasting of the waste generation. As the number of variables increases, traditional regression methods become inadequate for predictions. More complex techniques like Kernel-based Support Vector Machine (SVM) and Deep Learning offer superior results. In a study involving a private hospital in Antalya, Turkey, the quantity of medical waste was predicted using Kernel-based SVM and Deep Learning, considering variables like the number of surgeries, outpatients, inpatients, intensive care patients, and intensive care days. The models' performance was assessed using Root Mean Error (RMSE), Mean of Absolute Error (MAE), and R-squared.

Both algorithms yielded successful results, but Deep Learning (RMSE=0.094, MAE=0.079, R2=0.466) outperformed Kernel-based SVM (RMSE=0.264, MAE=0.202, R2=0.221). These algorithms demonstrate the ability to interpret the relationship between medical waste production and input variables, offers efficient support for medical waste management planning [42].

Deep MW, a deep learning approach (named) involves neural network ResNeXt, followed by transfer learning methods to improve classification results. The dataset consisted of labels, image data, and medical waste border for 3480 samples, which consisted of gauze, gloves, infusion bags, infusion bottles, infusion apparatus, syringe needles, tweezers and syringes. Various image augmentation techniques for different waste items were applied such as rotation, re-scaling, clipping, and flipping. The indicators that were used for the model results were f1 score, recall and precision [43]. A hybrid approach for waste classification employs three established CNNs – VGG19, DenseNet169, and NASNetLarge – to sort waste into six distinct categories, encompassing recyclable materials like metal, paper, plastic, and cardboard, as well as non-recyclable, medical, and biodegradable items [44]. This technique capitalizes on various CNN architectures, such as enhanced ResNext, YOLOv2, YOLOv3, ResNet-50, Auto Encoder with SVM, and MobileNet-V2, for waste classification tasks. A study addressed the critical issue of urban waste management within smart cities, proposed YOLOv3 deep learning algorithm to classify waste into biodegradable and non-biodegradable categories. The research involved creating a custom dataset and training the neural network to recognize six waste classes: cardboard, glass, metal, paper, plastic, and organic waste. The results underscored the effectiveness of the YOLOv3 algorithm in waste detection and classification for urban waste in public areas. Some complex waste items were grouped into a parent class to simplify recognition and reduce computational complexity. The study introduces a novel application of YOLOv3 for waste segregation, utilizing a dataset of 6437 waste product images. The comparison with YOLOv3-tiny revealed YOLOv3's superiority, highlighting the trade-off between accuracy and speed. Although YOLOv3 demonstrated higher average loss, it excelled in detection accuracy and prediction probabilities during testing. Despite minor challenges with occlusion and complex environments for smaller objects, YOLOv3 remains the preferred choice for tasks requiring high accuracy and reliability. This innovative approach holds promise for improving waste recycling and disposal in smart cities, and future research will focus on optimization and expanding the scope to include additional waste items [45].

In waste management beyond classification, a LSTM (Long Short-Term Memory) CNN predicts waste generation and carbon dioxide levels in bins, while a comprehensive CNN anticipates per capita waste production considering influencing factors, categorized as reusable, recyclable, or landfill waste. Automation is achieved through a camera-microcontroller-servo motor-equipped bin, guided by custom ResNet-34 software with multi-feature fusion and a novel activation function [46]. In the context of medical waste management, this methodology can be adapted to categorize medical waste efficiently. By training the CNNs on medical waste images, the system can accurately classify medical waste types like infectious, hazardous, pathological, pharmaceutical, and radioactive waste. This approach aids in the safe disposal and segregation of medical waste, minimizing health risks and environmental contamination [47,48]. Additionally, the LSTM CNN can forecast the volume of medical waste generated over time, enabling effective resource allocation and waste management strategies. Automated bins equipped with cameras and CNN-driven software can further enhance medical waste segregation, ensuring compliance with disposal regulations and optimizing healthcare waste processes. A seven layered Convolutional Neural Network (InceptionV3, MobileNetV2, MobilenetV3, ResNet50, ResNet101, Resnet152, Xception) integrated with machine learning techniques has been employed for biomedical waste classification in recent times. Seven cutting-edge CNNs and data pre-processing methods achieved validation accuracy of 91.9% to 94.6% across 9 waste categories. Notably, MobileNetV3 was selected as the final categorization method for BMW since it outperformed with a 95% accuracy, minimal storage (48 MB), and swift processing (260ms) [49]. Following the Cohort Intelligence (CI) algorithm, every hospital and depot is associated with the route; hospitals are considered as a node. Every hospital route is associated with the qualities, which were the distance and the risk associated with the environment. Comparative analysis and vehicle routing problem with the well-known optimization techniques were carried out, which ensured the timely and efficient collection and disposal of BMW [50].

Analytical Annotations for Biomedical Waste Generation

The prediction of the amount of BMW beforehand is conducive to its proper management. The size of the hospital, its location and capacity, the utilization rates, the number of surgical procedures number of inpatients and outpatients are predictor factors of medical waste generation. Conventional data management and predictive analysis involve statistical and mathematical analysis utilizing regression models and R studio [51]. Best-reduced model for predicting MWM cost for hospitals computes the medical waste generation rate by considering the hospital type and its location. In Turkey, MWM cost in selected hospitals was calculated using the variable pricing method; the mean medical waste generation rate for both per bed unit and per surgical procedure was predicted which could highlight the cost-saving strategies at the hospital level [52]. There are data-driven methods that follow a data-driven optimization model for BMW management during COVID-19 pandemic, since at that time the number of COVID patients was not certain. In the first phase, the number of patients in future periods was predicted by trained Artificial Neural Networks using the historical data, and a future scenario was forecasted and then reduced by the following K-Means method. The second phase was executed by two-stage stochastic programming, which was multi-objective, multi-period, and data-driven; conducted using the acquired scenarios of the previous phase. In a real case study conducted at Tehran city (Iran) during the COVID-19 pandemic, proper management of resources and an effective supply chain network design (SCND) were carried out. The forecasting was done following the K-Means clustering method, according to the patient's severity three clusters were formed, which were also correlated with three demand scenarios. Temporary healthcare facilities were suggested in the areas with high population density and an insufficient number of hospitals, for the treatment of Infectious Biomedical waste (IBW). Similarly, upon prediction, if the existing disposal facilities were not sufficient for processing of IMW, then temporary waste transfer centers were suggested [53]. Therefore, AI, IoT technologies, deep learning, machine learning, and neural networks in individual or combinatorial approach can be used for monitoring and management of bio medical waste management in the real time, summarized in Figure 2.

large amounts of data from various sources, such as sensors, social media, and satellite imagery, to predict waste generation patterns, identify hotspots, and forecast waste accumulation. These approaches can be applied without human intervention; effective in infectious situations

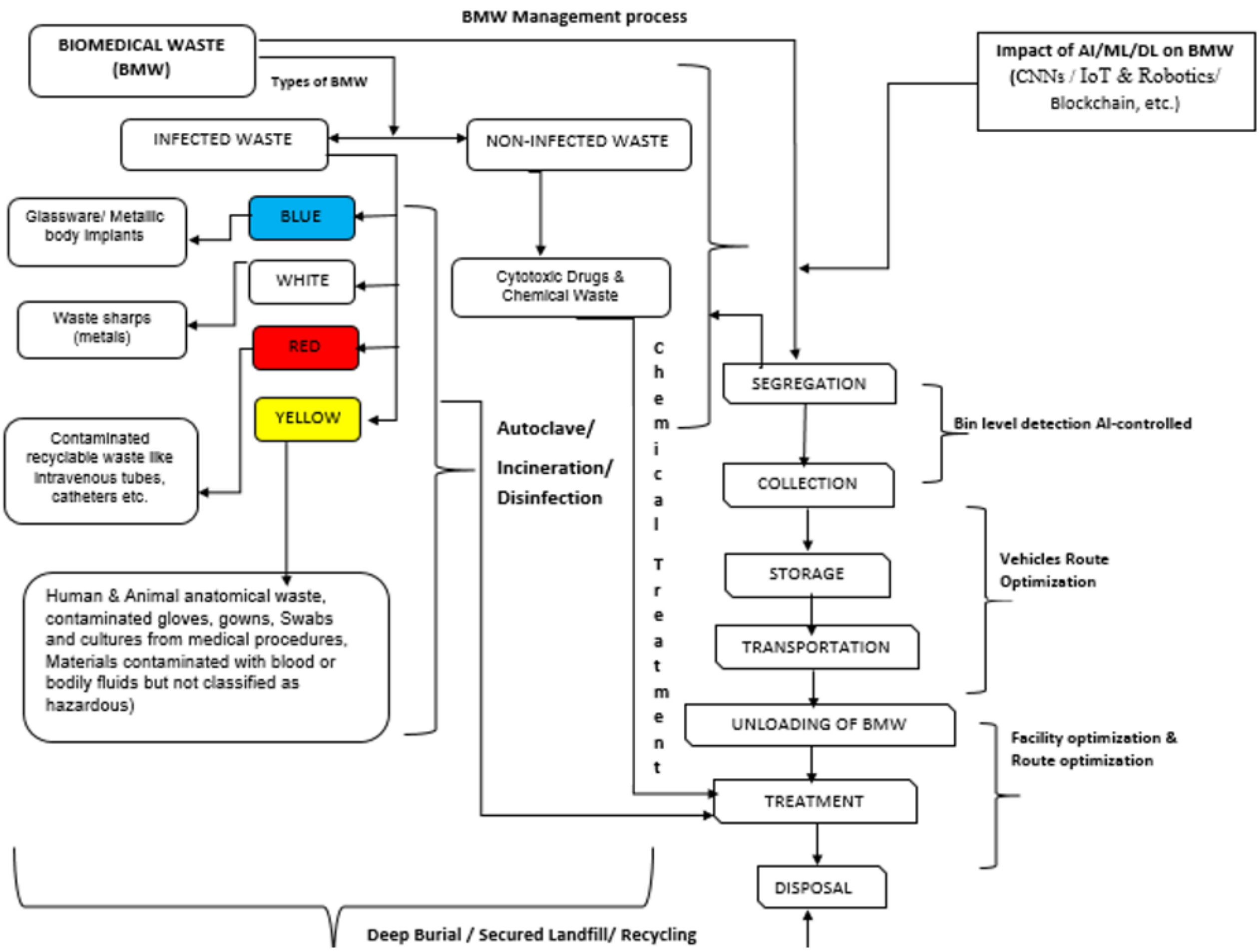

Figure 2) *Artificial intelligence, Internet of Things (IoT) technologies, deep learning, machine learning and neural networks in individual or combinatorial approach for management of biomedical waste management.*

Advantages of Artificial Intelligence in Biomedical Waste Management over Conventional Methods

As the local administration, waste management and maintenance services of cities all over the world are becoming smarter; automation and digitalization is also realizable in BMW. Artificial Intelligence (AI) has the potential to revolutionize waste management and can analyze such as COVID-19 pandemic. Hence AI can help in the optimization of waste collection routes, scheduling for collection, and resource allocation, which leads to reduced operational costs and energy consumption [54]. Hence the modernized management of biomedical waste Assisted with artificial intelligence has manifold advantages over the conventional methods, as listed in Table 1.

TABLE 1

Advantages of biomedical waste management assisted with Artificial Intelligent methods and tools

Aspects	Benefits of AI through different tools and techniques	Cited in Articles
Infection Risk Reduction	IoT sensors prevent waste bin overflow, while machine learning identifies infectious waste, robots manage it safely, and blockchain ensures secure disposal tracking for biohazard materials, safeguarding both public health and the environment [21,35,55-58].	Sharma *et al.*, 2020; Ahmad *et al.*, 2021; Murugaanandam *et al.*, 2018; Erdebilli and Devrim-İçtenbaş, 2022; Subramanian *et al.*, 2021; Sanabria *et al.*, 2023
Health Worker Safety	Artificial intelligence as a whole streamlines the handling of hazardous waste. IoT devices enable remote waste management for worker safety. Machine learning identifies and manages hazardous materials, and deep learning segregates dangerous substances. Robots perform perilous waste tasks, safeguarding workers, while blockchain monitors safety protocols during disposal, promoting transparency [35,59-63].	Ahmad *et al.*, 2021; Rubab *et al.*, 2022; Cheah *et al.*, 2022; Gupta *et al.*, 2023; Yang *et al.*, 2020; Bruno *et al.*, 2023
Pollution Reduction	IoT minimizes waste collection's environmental impact, while machine learning optimizes waste management to reduce pollution. Deep learning aids in toxic waste identification and disposal, and robots handle waste without pollution. Blockchain monitors and incentivizes eco-friendly waste disposal. Together, these technologies revolutionize sustainable waste management [64-68].	Yu *et al.*, 2021; Mohamed *et al.*, 2023; Gupta *et al.*, 2019; Alarood *et al.*, 2023; Kothari *et al.*, 2021
Waste Efficiency Boost	AI enhances waste management with streamlined processes, IoT sensors for efficient collection, machine learning optimization, deep learning automating sorting, continuous robot work, and blockchain automating billing/reporting. This synergy boosts efficiency, reduces downtime, and maximizes productivity in waste management operations [69-73].	Kurniawan *et al.*, 2022; Bommi *et al.*, 2023; Guo *et al.*, 2021; Song *et al.*, 2022; Bamakan *et al.*, 2022
Enhanced Bio-waste Safety	AI, IoT, machine learning, deep learning, robots, and blockchain technologies bolster data security and compliance in waste management. IoT ensures traceability, machine learning detects breaches, deep learning enhances disposal security, robots automate handling, while blockchain maintains transparent waste management records, collectively strengthening the industry's security framework [74-78].	Saini *et al.*, 2022; Qayyum *et al.*, 2021; Aazam *et al.*, 2018; Scott *et al.*, 2023; Wang *et al.*, 2021
Cutting Costs, Preserving	IoT minimizes fuel and labor expenses in waste collection, while machine learning optimizes resource allocation. Deep learning automates waste sorting, reducing costs. Robots enhance efficiency and decrease labor expenses. Blockchain streamlines administrative tasks, lowering administrative costs in waste management [27,79-81].	Fang *et al.*, 2023; Kargar *et al.*, 2020; Boudanga *et al.*, 2023; Gopalakrishnan *et al.*, 2021

Challenges and Ethical Considerations for Artificial Intelligence Mediated Biomedical Waste Management

The application of AI in BMW can pose vital challenges and ethical concerns. Algorithms learn from data, and biased training data can cause AI systems to unintentionally magnify prejudices [82]. Addressing bias in AI algorithms (e.g., linear regression, logistic regression, support vector machine, decision tree) ensures fairness. AI relies on extensive data for accurate learning, prompting privacy and security concerns [83]. Ensuring that data is collected and used ethically, with proper consent and protection mechanisms, the patient's security and privacy may be breached [84]. Many AI algorithms, particularly complex deep learning models, can be challenging to interpret and understand. The lack of transparency in decision-making processes can hinder accountability and the ability to address issues when the AI system makes incorrect or harmful predictions [85]. Transparent AI models and explainable AI techniques are vital to building trust and understanding. While AI has the potential to drive significant advancements and improvements in various fields, it's important to balance these advancements with responsible implementation. Rushing into deploying AI without considering the potential consequences can lead to unintended negative outcomes [86].

So to address these challenges and ethical considerations, the following steps to be taken care are (a) Ensuring that training data is diverse and representative of the population, can help to mitigate biases in AI algorithms (b) Conducting regular audits of AI systems to identify and rectify biases and other ethical concerns (c) Implementing techniques like federated learning and differential privacy to protect individuals' privacy while still benefiting from collective data (d) Developing AI models that provide explanations for their decisions, allowing stakeholders to understand the reasoning behind predictions (e) Governments and organizations can establish regulations and guidelines for AI development and use to ensure ethical practices are followed (f) Establishing independent review boards to assess and approve the deployment of AI systems in critical domains (g) Regularly monitoring AI systems in real-world scenarios and continuously improving them based on feedback and performance. In essence, these challenges and ethical considerations emphasize the need for a holistic and responsible approach to AI development, where innovation is balanced with social and ethical concerns [87]. This approach will help ensure that AI technologies contribute positively to society while minimizing potential risks [88].

Future Directions and Recommendations for AI Mediated Bio Medical Waste Management

To ensure effective and sustainable management of biomedical waste, several future directions and potential advancements can be considered. These advancements will not only enhance waste disposal methods but also contribute to minimizing the environmental and health risks associated with improper waste handling [89]. Next-gen biomedical waste management may merge drones and remote sensing for ongoing surveillance of waste processes. This entails monitoring generation, collection, transport, and disposal, allowing real-time data-driven resource allocation, interventions, and compliance oversight [1]. AI predictive models forecast biomedical waste using factors like population density, diseases, and healthcare activities. This aids waste systems in anticipating needs, optimizing routes, and efficient resource allocation. Machine learning refines sorting, boosting recycling and disposal [90].

More advancement is required in Autonomous robots with AI and sensors. The futuristic Blockchain technology can establish a transparent record of waste management, ensuring proper disposal, tracking, and verifiable compliance data [91]. Advanced waste-to-energy technologies could be explored to convert biomedical waste into clean energy sources, such as biogas or electricity. This not only addresses waste disposal concerns but also contributes to sustainable energy generation.

Future progress requires strong regulations for handling biomedical waste, spanning its disposal and transportation. Policymakers must match the advancements in technology, should align the waste practices with health and environmental goals. As technology evolves, public education will vitalize responsible biomedical waste management among providers, patients, and the public. Effective communication on hazards of improper disposal and the benefits of smart waste solutions can induce behavioral shifts. Since biomedical waste challenges transcend borders, international collaboration and knowledge sharing can facilitate the exchange of best practices, technological innovations, and regulatory experiences to create a more comprehensive and effective approach to waste management on a global scale [21].

Conclusion

In the realm of biomedical waste management, the landscape is evolving at an unprecedented pace, driven by the integration of Artificial Intelligence (AI) and cutting-edge technologies. This transformative shift is essential, as conventional methods have proven to be inefficient and cumbersome in handling the challenges posed by biomedical waste. The last decade has witnessed the emergence of AI-powered solutions, offering a beacon of hope for more efficient, cost-effective, and environmentally sustainable management. AI, in tandem with wireless detection, Internet of Things (IoT), and machine learning, has paved the way for intelligent waste monitoring, predictive waste generation models, and optimized resource allocation. These advancements not only promise substantial cost savings but also ensure better risk management and resource optimization. The real-time monitoring of biomedical waste has been improved with the use of mobile applications, use of drones and remote sensing. Predictive models for waste generation are now amalgamated with technological interventions and leads to the optimization of resources for biomedical waste management. Moreover, technologies like blockchain, RFID tags, and robotics are adding transparency and traceability to the entire biomedical waste management process, while smart trash bins equipped with AI has streamlined the waste sorting. As we look to the future, it's imperative that strong regulations and international collaborations should go hand in hand with these technological advancements. Public education and awareness campaigns will also play a vital role in instigating responsible biomedical waste management. In conclusion, the integration of AI in biomedical waste management is a beacon of hope, promising a cleaner, greener, and safer world for all, safeguarding the public health and environment. The incorporative journey of AI in biomedical waste management has begun; all stakeholders, from healthcare professionals to policymakers and general public would be collectively responsible for its effective implementation in future.

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