International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://theaspd.com/index.php

Improving Public Health Through Effective Biomedical Waste Management: A Comprehensive Review

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abstract
The volume of biological face masks, too, has ballooned due to the COVID-19 pandemic; it was a significant factor in places that had seen a high level of healthcare activity, such as Nashik in the state of Maharashtra. The paper analyzes the difference in the quantity of biomedical waste generated at Nashik, which occurred before and after the epidemic (May 2020 to March 2024). The findings reveal a substantial increase in waste generation, primarily due to the increased use of medical supplies, including personal protective equipment (PPE), diagnostic test kits, and other medical disposables. This increase has highlighted challenges with waste management facilities, waste segregation protocols, and, once again, compliance issues. To mitigate risks to public health and the environment, the report recommends enhanced waste management methods, including improved sorting, processing, and disposal of waste. Modern technology applications, alongside improved public education and health worker training, are expected to be one of the highest priorities for improving bio-waste management. This report also suggests several measures to address the issues caused by the long-term effects of the pandemic on bio-medical waste management. The elimination of waste will better protect human health and the environment from potentially harmful contaminants.
Keywords: *COVID-19; Biomedical Waste; Waste Management; Healthcare Facilities; Waste Segregation; Treatment Technologies*

1. INTRODUCTION

The world economy, healthcare, and environmental sustainability are among the various sectors that have all experienced a drastic impact from the COVID-19 pandemic, which emerged in late 2019 [1]. It has also been one of the most noticeable effects of this epidemic: the proliferation of bio waste. "Biomedical waste" means any discarded trash created when diagnosing, treating, or immunizing humans or animals. The improper management of sharps, contaminated dressings, and laboratory waste can have a detrimental impact on human health. Indian healthcare providers were having a hard time, even before the epidemic, handling biomedical waste appropriately. The rapid increase of COVID-19 cases elevated the consumption of PPE, test kits, and other medical supplies, resulting in a significant rise in the amount of biomedical waste generated (Fig. 1). There were concerns on the management and disposal of such hazardous waste due to the overwhelming number of health care facilities, including hospitals [2].

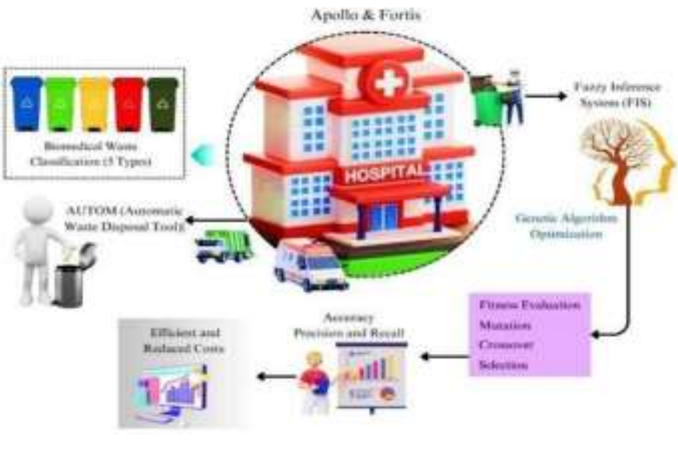


Figure 1: Biomedical waste [3]

In the fast-growing city of Nashik, Maharashtra, India, numerous healthcare facilities are available, including hospitals, dispensaries, and dialysis centers [4]. The outbreak has significantly impacted the generation of waste in the area. It has increased awareness of the causes of biomedical waste, the need for effective waste management, and measures to protect public health and the environment from potential hazards. Therefore, a current study was conducted to assess the effect of the COVID-19 pandemic on biomedical waste production in Nashik, comparing data from before and during the pandemic. To provide more insight into the disinfection and disposal of biomedical waste during this unprecedented emergency, an analysis was conducted on the amount of waste disposed of, the disposal methods employed, and compliance with regulations [5]. The findings will support the development of improved waste management strategies, helping to protect ecosystems and enhance public health in the post- epidemic period. Proper disposal of biomedical waste is crucial for safeguarding both the environment and public health. Healthcare institutions generate vast amounts of waste that is likely to be harmful. Effective management avoids infectious disease outbreaks and exposure to dangerous materials that contaminate water and soil sources. When properly disposed of, biomedical waste shields medical personnel from potentially harmful microorganisms. It also helps protect the neighborhood from health hazards caused by improper waste management [6]. What does biological waste management include, and what rules apply? Regulatory agencies have established protocols for the efficient handling of biomedical waste. Observing these rules reduces the likelihood of facing legal action and incurring fines. In a healthcare facility, efficient waste management promotes a culture of accountability and safety. Staff training includes waste identification, segregation, and proper disposal. Adopting best practices is sustainable because it won't strain the treatment facilities. Advanced technologies, including autoclaving and incineration, ensure the safe disposal of waste. Public awareness efforts will also help communities understand the importance of effective waste management. Community participation in maintaining a clean environment is a key outcome of such programs. Health facilities need to make infrastructure investments because maintaining hospital infrastructure for biomedical waste management and staff training is crucial. By doing this, they protect the environment and their patients and employees. In summary, proper disposal of biological waste is essential for environmental protection, public health, and legal compliance [7].

1.1. Understanding biomedical waste

Biomedical waste management is very important because if it is not done correctly, it can harm people and the environment [7], [8]. As of 2023, India produces approximately 700 tons of biomedical waste per day (TPD). The country can only process 1,590 tons of this type of trash. However, only around 640 TPD is being processed properly, indicating that a gap still exists between the amount of trash generated and its disposal [9]. Additionally, as of mid- 2024, only 156,540 of India's more than 393,000 healthcare facilities had been formally approved by State Pollution Control Boards (SPCBs) or Pollution Control Committees (PCCs) [10]. The absence of permission makes it much harder to track and manage waste. In April 2025, the Central Pollution Control Board (CPCB) announced new rules that biomedical waste treatment plants had to follow to ensure consistency and environmental protection [11].

1.1.1. Biomedical Waste

Proper management is only possible by accurately identifying the different types of biomedical waste, ranging from infectious materials to hazardous chemicals generated from various sources, such as hospitals, clinics, or laboratories. Such identification helps in developing the appropriate methods for their disposal and treatment [12]. Waste resulting from, or caused by, medical procedures related to diagnosis, treatment, immunization, or pharmaceutical use of humans or animals is known as biomedical waste. The primary industries where this occurs most frequently are clinics, hospitals, labs, and research institutes. These facilities generate various waste products, ranging from pathological waste (including tissues and organs) to sharps (such as scalpels and needles) [13], [14]. Chemical waste, abandoned medical equipment, and pharmaceutical items are added to the dustbins. Hospital trash has various hazards. Hence, specific methods for handling and disposing of it have been developed to reduce risks. For instance, hospitals should handle pathological wastes using cutting-edge techniques, and healthcare personnel should dispose of sharp wastes in containers that can withstand punctures. The disposal process is simplified by ensuring that different types of waste do not mix, thanks to proper source segregation [15]. A healthcare professional should properly separate the trash; training programs and unambiguous instructions help them with this enormous responsibility. Healthcare facilities must be aware of the various types of biomedical waste and their sources to protect the environment and public health from potential risks associated with biomedical waste [1], [2]. The goal of biological waste management is proper management, which can only be achieved with the maximum cooperation of cautious and knowledgeable healthcare personnel who adhere to established guidelines [16].

1.1.2. Types of Biomedical Waste

Based on its origin and hazards, biomedical waste is divided into several categories, including radioactive, hazardous, general, and infectious waste. Used needles, surgical equipment, and lab cultures are examples of objects contaminated with pathogens that are considered contagious waste because they present a danger of infection to humans and the environment [17]. The term "hazardous waste" describes substances such as contaminated sharps, medicines, and certain chemicals that can be potentially toxic, corrosive, or reactive. Like domestic waste, general waste comprises non-hazardous items, such as food scraps and packaging, that don't directly endanger people but still need to be disposed of properly. Finally, materials produced by radioactive isotope-based therapeutic and diagnostic operations are included in radioactive waste, which requires careful management and disposal methods to minimize radiation exposure. The need for appropriate segregation, treatment, and disposal techniques in healthcare settings is emphasized because each type of biomedical waste requires particular management approaches to assure safety and compliance with regulatory standards [18], [19]. Each type of biomedical waste requires specific handling. India's biomedical waste market is expanding, valued at USD 286.98 million in 2024 and projected to reach USD 486.09 million by 2033, growing at a CAGR of 6% [20]. The adoption of advanced technologies—such as autoclaving, microwave disinfection, and pyrolysis—is becoming more common, offering safer and environmentally friendly alternatives to traditional incineration [21]. The need for appropriate segregation, treatment, and disposal techniques in healthcare settings is emphasized because each type of biomedical waste requires particular management approaches to assure safety and compliance with regulatory standards [20], [21].

1.2. Regulatory Framework

In 1998, the BMW rules were created by the Ministry of Environment and Forests, Government of India, to streamline waste treatment, disposal, and handling, thereby minimizing the risk to human health and the environment. In 2000 and 2003, these regulations were revised. To avoid harm to people and the environment, these changes aim to set up rules for how BMW from healthcare facilities (HCFs) throughout the nation should be transported, stored, treated, and disposed of [22].

1.2.1. National Guidelines for BMW Management

Copies of the National Guidelines on Hospital Waste Management were sent to all states and union territories under the existing Bio-medical Waste (Management & Handling) Rules, 2002. As required by the IMEP for policy direction, national strategy reports on biomedical waste management were published to provide guidance to health facilities at all levels. The CPCB issued guidelines for building incinerators and Common BMW treatment facilities. State Pollution Control Boards (SPCBs) in the Union Territories, along with the Pollution Control Committees, monitor biomedical waste. In these, a set of guidelines existed in 1998, along with amendments in 2000 and 2003 [17], [18], [19]. However, since health is a state subject, the relevant state government must initiate the necessary steps to ensure compliance. They are empowered to enforce these Rules. According to the aforementioned National Guidelines for Hospital Waste Management, the hospital administrator shall establish and oversee a waste management committee. Biological waste handlers will have their security guaranteed. The Rubbish Management Committee meetings will evaluate the effectiveness of garbage collection. This Committee supervises the preparation, implementation, and monitoring of hospital-specific waste management action plans [19].

1.2.2. Norms and Best Practices

For the protection of the public and the environment, effective biomedical waste management is crucial, particularly in healthcare facilities where hazardous waste is generated. Dividing waste at the generation site into discrete categories, such as infectious, non-infectious, sharps, and recyclable materials, and utilizing containers with clear labels are one of the best practices for managing biomedical waste. Training personnel on correct handling, storage, and disposal techniques are crucial to minimize risks. Before being disposed of, waste must be cleaned up using techniques such as autoclaving or incineration, in accordance with local laws and standards established by agencies like the Environmental Protection Agency (EPA) and the World Health Organization (WHO). Waste management procedures are regularly audited and monitored to identify areas for improvement and ensure compliance [22]. Furthermore, educating the public and healthcare professionals on the significance of biological waste management can significantly lower the risk of contamination and environmental damage [23].

1.2.3. Regulatory and Infrastructure Enhancements

Common Biomedical Waste Treatment Facilities (CBWTFs): As of 2023, India had 218 operational CBWTFs, with an additional 34 under construction. These facilities centralize the treatment and disposal of biomedical waste from multiple healthcare establishments, ensuring standardized processes and reducing environmental impact [24].

Central Pollution Control Board (CPCB) Guidelines: In April 2025, the CPCB issued mandatory guidelines for CBWTFs, emphasizing uniform standards in site selection, facility design, waste transportation, and treatment protocols. These guidelines aim to strengthen biomedical waste management across India [25]. 1.2.4.Market Trends and Technological Innovations Market Growth: The biomedical waste management market in India was valued at USD 286.98 million in 2024 and is projected to reach USD 486.09 million by 2033, growing at a CAGR of 6.00% [26].

Technological Advancements: Innovations such as autoclave sterilization, microwave-based treatment, and pyrolysis are gaining traction, replacing conventional incineration methods. These technologies enhance safety, minimize environmental impact, and enable resource recovery, such as energy generation from waste [26].

1.2.5. Challenges and Areas for Improvement

Treatment Capacity vs. Generation: India generates approximately 700 tons per day (TPD) of biomedical waste, while its treatment capacity stands at 1,590 TPD. However, only 640 TPD is treated, indicating a gap between waste generation and treatment [27]. Public Awareness and Training: There is a need for increased awareness and training among healthcare professionals regarding the proper segregation and disposal of biomedical waste. Studies indicate variations in knowledge, attitudes, and practices toward biomedical waste guidelines among healthcare professionals, which can affect patient care and safety [28].

1.3. Biomedical Waste Management Practices

Biomedical waste management practices encompass a range of strategies and methods aimed at safely handling, processing, and disposing of waste generated by healthcare facilities, including clinics, hospitals, laboratories, and research centers. Hazardous materials, such as infectious waste, sharps, chemicals, and medications, may be present in this garbage. If not pro perly managed, these materials pose a threat to the environment and public health. The separation of waste at the source, using colour-coded containers for various types of waste, and staff training on appropriate disposal techniques are all essential components of efficient biomedical waste management. Before garbage is disposed of, treatment methods such as chemical disinfection, autoclaving, and incineration are used to reduce the amount and toxicity of the waste. Regulatory compliance is essential, as many nations have imposed strict regulations on the treatment of biological waste to safeguard public health, professionals, patients, and the environment. An efficient biological waste management system must include regular audits, monitoring, and reporting to guarantee continual progress and adherence to best practices [29]. In Delhi, for instance, approximately

31.2 metric tons of biomedical waste are generated daily. The city operates two Common Biomedical Waste Treatment and Disposal Facilities (CBWTFs) with a combined daily processing capacity of 62.8 metric tons. Despite this capacity, experts emphasize the need for regular monitoring, audits, and facility expansion to prevent unauthorized disposal and illegal incineration [30].

1.4. Treatment of Biomedical Waste

"Treatment" refers to changing garbage before sending it to its destination. The point of generation should be the site of treatment. Waste must be treated to render it safe and cease to be a source of pathogens. Bleaching, shredding, and chemical disinfection are among the procedures. The Indian government has published a set of regulations for handling trash. The leftovers can be disposed of at their designated location after treatment. Typical waste treatment methods include [29]:

1.4.1. Treatment of wastes

Syringes and needle nozzles should be cut into syringe cutters or needle destroyers (Fig. 2). Glassware needs to be sanitized, cleaned, and sterilized. Store shattered glass, razors, blades, and scalpels in a container that can withstand punctures and be filled with bleach. Then, it is placed inside a cardboard or plastic box with a label. Before sending these boxes to incubators, they should be sealed to stop spills. Culture plates are disposed of in the designated bags. Additionally, plates need to be sterilized after autoclaving. Reusing sterilized plates is possible. It is necessary to cut, mutilate, shred, and destroy gloves before disposing of them.

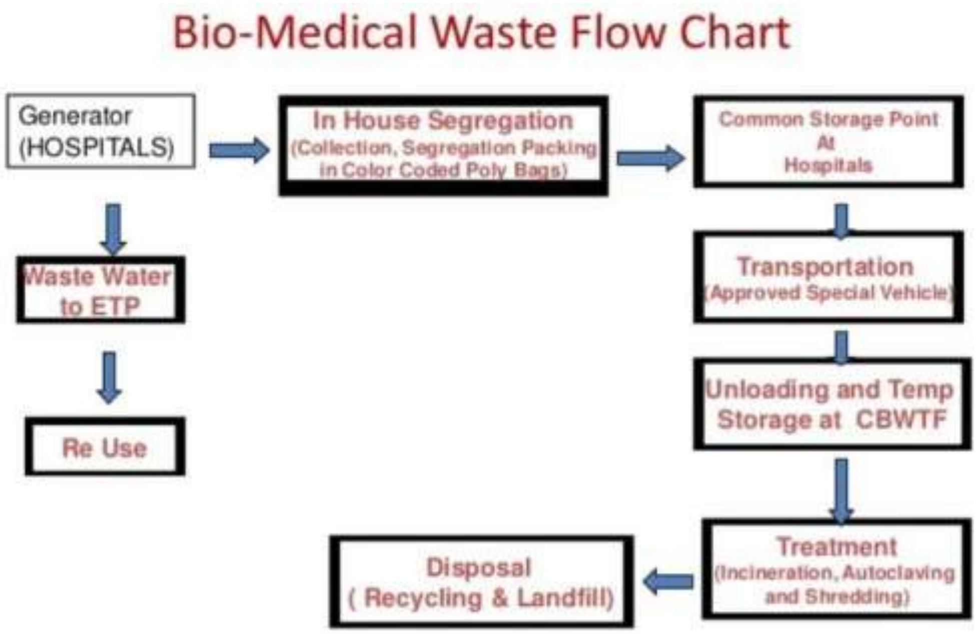


Figure 2: Biomedical waste treatment [30]

The Central Pollution Control Board (CPCB) has issued comprehensive guidelines for the establishment and operation of Common Bio-medical Waste Treatment and Disposal Facilities (CBWTFs). As of 2023, 234 CBWTFs are operational across India, with an additional 30 under construction. These facilities are central to minimizing environmental contamination and ensuring public health safety [31]. In terms of disposal methods, the CPCB reported that in twelve states and Union Territories, CBWTFs are exclusively used for the treatment and disposal of biomedical waste. In contrast, in the remaining regions, captive treatment facilities and deep burial methods are still employed alongside CBWTFs. Deep burial, permitted only in rural or remote areas with prior approval from the relevant state pollution control board, involves placing biomedical waste in a pit or trench, covering it with soil and lime [32].

1.5. Objectives of the study

To examine the patterns in Nashik's production of biomedical waste both before and after the COVID-19 outbreak. To assess how the pandemic has impacted the quantity and management of biological waste in the area. To list the difficulties in managing biomedical waste during the epidemic and recommend possible enhancements. To evaluate the connection between public health outcomes and biomedical waste management practices.

2. LITERATURE REVIEW

D'Souza (2025), in the edited book Solid Waste Management: A Roadmap for Sustainable Environmental Practices and Circular Economy by Springer Nature, "Revolutionizing Biomedical Waste Management: Embracing Innovative Technologies for a Healthier Future" was published. This article examined how new technologies could transform the systems for handling biomedical waste. Their study emphasized the need to move beyond conventional waste disposal methods, including burning and autoclaving, into the realm of smart technologies such as artificial intelligence (AI), discussed how digital monitoring apparatus could aid in real-time tracking, prevent illegal dumping, and ensure adherence to regulations by making it easier to track. Plasma pyrolysis, microwave irradiation, and enzyme-based biodegradation technologies were also considered as long-term alternatives with less environmental impact. Dsouza et al. said that new ideas like these, if supported by laws and infrastructure, could significantly reduce the risks to workers' health and the environment, and make BMWM aligned with the principles of a circular economy. These initiatives demonstrated a forward-thinking approach that recognized technology as a vital resource for driving more efficient and environmentally friendly waste management in healthcare [33].

Hajam and Lata (2025) in Biomedical Waste Management, published by Apple Academic Press, provided an extensive review of the concepts used in BMWM systems. They also examined the entire waste management cycle, covering sorting and colour-coding, storage rules, handling methods, transportation regulations, and final disposal solutions. The first stage of treating biomedical waste properly is to segregate and identify it at its source, they said.

The researchers examined legal guidelines, including the WHO guidelines and state laws. They emphasized that following these rules could dramatically reduce the risks to workers and the environment. Hajam and Lata also examined various treatment technologies, including autoclaving, incineration, deep burial, and chemical sterilization, and discussed the advantages and disadvantages of each. They argued that the human aspects of work, training, accountability, and organizational culture were just as important as the technology in determining the extent to which BMW initiatives were effective [34].

Hamed et al. (2025) had also investigated how nurses themselves can influence the management of biomedical waste. Their study, published in BMC Nursing, transcended technical frameworks to consider the human aspects of BMWM, specifically nurses' knowledge, attitudes, and practices. The study showed that appropriately trained and informed nurses were crucial in ensuring that rubbish was segregated, labelled, and handled adequately within clinical areas.Hamed and his colleagues stated that hospitals require long-term training programs, continuous professional development, and organizational support to foster a culture of safety and a sustainable environment. They decided that empowering nurses may bring about transformations with regard to the biomedical waste management in general and will be conducive to better healthcare and safer patients [35].

Anawade (2024) discussed the existing problems associated with current techniques for biomedical waste management. The BMWM process, which the researchers presented in the AIP Conference Proceedings, includes separating waste, collecting it, transporting it to a facility, treating and disposing of it. They emphasized that bad sorting at the source, particularly in healthcare facilities, was a major issue that undermined the entire waste management system. Healthcare personnel not knowing the rules well enough and not adhering to them were also among the highest perceived causes of error, as were health considerations, the authors noted. The study found that biohazard requirements should be more effectively enforced, and new technologies, such as GPS tracking and digital waste monitoring systems, may facilitate the process of tracking waste to ensure compliance with rules [36].

Singh et al. (2024) took a broader perspective on the impact of inappropriate disposal of biomedical waste on public health in their study, which was published in Discover Applied Sciences. The authors aimed to demonstrate that sound BMW principles could contribute to a cleaner and safer environment. Their findings highlighted the importance of having a sound policy framework that links government regulations with community engagement. Good biomedical waste management, they said, might not only reduce health hazards, but also significantly help control environmental pollution. The report recommended strategic interventions, including decentralized waste treatment units, real-time monitoring, and skilling programs for healthcare personnel. The authors also noted that BMWM practice at the hospital should align with national and worldwide sustainability objectives. They noted that this would have a large impact on long-term environmental health and resilience [37].

Omo and Hassan (2024) provided an important environmental perspective in advanced Engineering Technology and Sciences. In their study, the researchers examined the cumulative effect of biomedical waste on the environment, specifically when it is disposed of in a landfill, burned with inadequate filters, or left untreated. The authors described how uncontrolled BMWM systems led to soil contamination, water pollution, and toxic air shame. They also discussed how sharps, infectious products, and hazardous chemicals can harm both ecosystems and people. Omo and Hassan proposed the application of advanced. They emphasized that environmental audits, eco- labelling of health-care institutions, and increased judicial accountability would be required to ensure compliance with environmental safety standards [38].

Dhole (2024) examined the current state of biomedical waste management in India. Their study, published in Cureus, examined the structural and functional issues that continue to obstruct the effective implementation of the Biomedical Waste Management Rules (2016). The authors observed that, although regulations existed, they were not always enforced due to a lack of administrative oversight, low priority given to waste control in healthcare budgets, and the absence of oversight. The lack of common biological waste treatment facilities (CBWTFs) was a major issue in rural hinterlands, they added, warning that practices such as unsafe burial, open dumping, and burning of town rubbish, which comprises hazardous materials, have become a public health risk. Dhole et al. also stated that the urban tertiary care centers may have taken initial steps to apply standard waste separation and disposal approaches at their facilities; however, smaller clinics, diagnostic centers, and rural health posts did not frequently have the capacity and systems in place to comply with the legislation [39].

Eiffel (2027) approached the issue of hospital waste management with a multi-tier decision-making model that aimed to sustainably plan for the future (2017). Their study, published in the journal Sustainability, involved several multi-criteria decision-making (MCDM) components including the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and they were employed to rank various
waste treatment techniques (including, irradiation, chemical disinfection, autoclaving, and microwave treatment) from worst to best. The study examined several factors, including cost-effectiveness, environmental impact, reducing waste, technological feasibility, and safety. The writers emphasized that no single strategy could be the best for everyone and that optimal results could only be achieved by balancing the needs of the environment, the economy, and operations. They also pushed for decision-making that included all stakeholders. They suggested that including healthcare professionals, lawmakers, engineers, and waste management workers in the review process might lead to more practical solutions that take the situation into account. The framework of the study not only provided a strong way to improve biomedical waste treatment solutions [40].

Rathod (2024) published a comprehensive review that addressed the issue of biomedical plastic waste. The authors examined the sources, risks of microbial contamination, treatment options, and recycling potential of plastic-based waste, including syringes, PPE kits, IV bags, and tubing. They did this because they knew that plastics made up a significant portion of total biomedical waste, especially following the COVID-19 pandemic. Their investigation found that the growing use of single-use medical plastics has led to a significant increase in non-biodegradable waste, much of which remains unprocessed or is improperly disposed of. They explored several methods for disinfection, including autoclaving, ultraviolet light, microwave heating, and chemical treatment. They tested all of these to see how well they worked at killing microbes without breaking down the material so much that it could no longer be recycled. The scientists also examined recycling methods that can be employed after treatment, including pyrolysis, gasification, and mechanical shredding. They advocated for a circular economy model, in which biomedical plastics could be safely treated and then reused in industry. They concluded that hospitals, municipalities, waste treatment companies, and environmental regulatory agencies will be required to cooperate in improving the management of biomedical plastic waste [41].

Kukreti (2024) contributed to the analysis with the chapter "Biomedical Waste: Environmental Impacts and Sustainable Management" in the book Biomedical Waste Management: Bioremediation and Recycling. The environmental impact of biomedical waste was thoroughly examined, particularly in relation to the air, water, and soil systems. The authors studied hazardous releases (including dioxins and furans), soil contamination, and microbiological hazards resulting from improper disposal methods, such as open burning, loose landfilling, and the discharge of untreated effluent. The research also highlighted an issue with microplastic pollution involving the disposal of PPE and medical packaging. It observed the potential long-term effects of this on marine ecosystems and food chains. Kukreti et al. also investigated the effectiveness of bioremediation techniques, such as microbial degradation and phytoremediation, as environmentally friendly options to conventional remediation processes. Their research examined how policies that incentivize sustainability, institutional responsibility, and public and commercial collaborative partnerships could mitigate the environmental impact of biomedical waste. An integrated management system, which includes reducing waste, safely treating medical waste, reusing safe waste, and protecting public health, has been advocated for effective biomedical waste management in an eco-friendly manner [42].

Mishra et al. (2024) examined the state of Indian smart cities and their responses to the COVID-19 pandemic. The study focused on completed and ongoing initiatives under the Indian government's Smart City Mission, which, when combined with other measures, has significantly aided pandemic containment. According to the report, contemporary cities in both affluent and developing nations struggled to respond sufficiently during the epidemic because they were ill-prepared to handle emergencies. According to a review of primary and secondary data, the most beneficial initiatives for monitoring COVID-19 cases were digital surveillance and mobility control via integrated control command centers (NIC). However, the efficient use of established initiatives is hampered by the absence of technological integration in smart cities. Therefore, the study suggests network-based integrated apps for mobility, HealthCare, basic services, and moving throughout India's smart cities. The suggested framework is anticipated to give innovative city framework designs the much-needed alignment at the policy, goal, and implementation levels [43].

Liladhar et al. (2023) assessed a viable location for a sustainable housing development in Nashik, India. This study employs the multi-influence factor (MIF) technique, based on geographic information systems (GIS), to identify optimal sites for future urban development. Eleven criteria formed the basis of the assessment: vegetation, elevation, land use, industry, drainage system, slope, bodies of water, roads, medical facilities, train station, and population density. The sustainable site appropriateness was determined by combining all components taken into account, along with corresponding MIF weights, and considering the interrelationships between the factors. According to the findings, 27.26% of the study area was not optimal for developing settlements, 16.82% was of low suitability, 30.65% was of moderate suitability, 16.48% was of high suitability, and 8.77% was of extremely high suitability.

Most good locations were close to the main thoroughfares and the current population area. The receiver-operating characteristic (ROC) curve was used to validate the suitability of the sites, and an area under the curve (AUC) value of 0.895 indicated that the model was effective. Sensitivity analysis revealed that the primary factors influencing the optimal location for settlement growth in the research region are proximity to roads, drainage systems, and health services. Soon, planners and policymakers will find the results of the identified optimal regions for intense urban settlement development, which will help promote sustainable urban expansion [44].

Kaurand Pandey (2021) discussed the potential adverse health effects of concentrations of aerosols and PM, as well as particles that people inhale and allow into their respiratory systems. Grave concerns about air pollution and climate change have been raised in various parts of the world. Considering the dire consequences of air pollution and climate change on human health, an assessment was conducted of an Indian city. The emerging metropolitan regions pose health hazards, including extreme weather conditions such as droughts, floods, and heavy rains. Due to the increasing frequency of heat waves, city residents have faced several health issues, including thermal discomfort. For most Indian megacities, this report focused on the rising levels of air pollution that were above acceptable limits. Another study assessed the health effects of the COVID-19 lockdown on city residents. Urbanization, air pollution, and global warming seemed to have interlinked connections. Aerosols and other air pollutants affect Earth's climate directly through absorption and scattering. Indirectly, aerosols altered cloud properties and the processes involved with radiation transfer. Consequently, policymakers referred to the review as a base data source when evaluating vulnerable areas and implementing control measures for air pollution. Based on the review of Indian cities, adaptation and mitigation plans can be developed to combat climate change and mitigate the adverse health impacts through regular air quality monitoring [45].

Gangwarand Ray (2021) examined COVID-19 cases in India during the pandemic's PLD, LD, and UL periods. On March 11, 2020, the COVID-19 pandemic was officially declared a global health emergency by the World Health Organization due to the widespread sicknesses. Investigations were conducted at the regional, state, and government levels using geospatial innovation. In contrast to the US, different nations had far higher infection rates. In the UL4.0-UL5.0 stages, India's infection rate was second only to the USA; in the PLD-UL5.0 period, it was the most noteworthy among SAARC member states; and in the UL2.0-UL3.0 stages, it was the third most noteworthy worldwide, behind only Brazil and the USA. India's eastern, southern, and western focal pieces often have higher counts. Population thickness was demonstrated to be connected with the pattern in COVID-19 cases. The mortality cost in India was below the worldwide average throughout the investigated pandemic period. The most significant number of sicknesses was reported during PLD in Kerala, while the largest was reported in Maharashtra during all LD and UL stages. The densely populated areas of India accounted for 80% of the cases. The leading 25 areas were responsible for 70.99%, 69.38%, 54.87%, 44.23%, 40.48%, and 38.96% of the infections from the very outset of UL1.0 to the furthest limit of the UL stages in that request. The fact that 6.38 per cent, 6.76 per cent, 11.23 per cent, 12.98 per cent, 13.40 per cent, and 13.6 per cent of cases occurred in the leading 26-50 areas during the UL time frame indicates that COVID-19 spread throughout that period. As of October 31, 2020, the urban communities of Bengaluru Metropolitan, Chennai, Thane, Mumbai, and Pune had the lowest number of diseases, while Delhi had the highest. The infection rate in India remained unaltered even at UL5.0, which is an exceptionally worrying situation [46].

3. METHODS

3.1. Data

Statistics can also capture the volume of biomedical waste produced by each Indian state and union territory from May 2020 to March 2024. Data like this enables one to track specific trends regarding the COVID-19 pandemic's impact on waste production, thus informing waste management and disposal techniques [47].

3.2. Literature for this study

The researchers accessed peer-reviewed articles from journals indexed in the Scopus and Web of Science databases to assess the amount of healthcare or biomedical waste generated by the COVID-19 pandemic. They also gathered the latest data, guidelines, tables, and posters on the BMW management, treatment, and disposal of COVID-19 waste by accessing the official websites of the health ministries, public domain platforms, and pollution control boards. This comprehensive analysis aimed to understand how the pandemic impacted BMW, highlighting the importance of effective management practices in line with updated regulations.

3.3. Generation of Bio-Medical Waste (BMW) in India Pre-COVID-19 Outbreak

India produces around 619 tonnes per day of BMW. Figure 3 depicts city-wise BMW production in 2023.

International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://theaspd.com/index.php

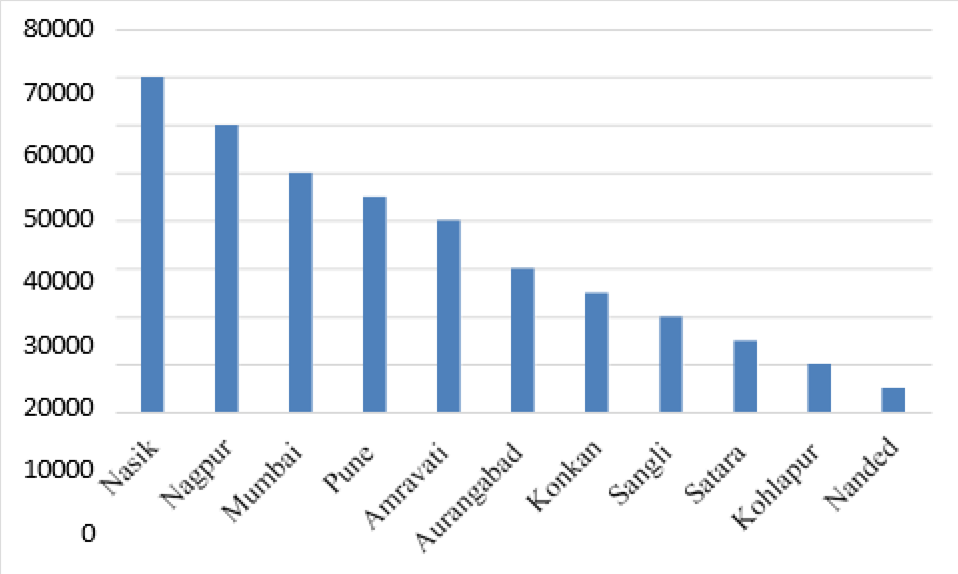


Figure 3: BMW generation in different cities of Maharashtra in 2023 [48]

However, several sources provide insights into the trends and management of biomedical waste in the state [48]: Maharashtra has historically been a leading state in biomedical waste generation. Between June 2020 and June 2021, the state generated 8,317 tons of biomedical waste, representing a significant increase from 62.3 tons in the 2019-20 fiscal year. During the COVID-19 pandemic, Maharashtra was responsible for approximately 17% of India's COVID-19-related biomedical waste [49]. Districts such as Mumbai, Pune, Thane, Nashik, and Nagpur have been identified as major contributors to the generation of biomedical waste. These areas are characterized by high population densities and numerous healthcare facilities, resulting in increased waste volumes. Maharashtra operates 31 Common Biomedical Waste Treatment and Disposal Facilities (CBWTFs), including 29 incinerators, to handle the state's biomedical waste. The Maharashtra Pollution Control Board (MPCB) oversees the authorization and monitoring of healthcare establishments generating biomedical waste, ensuring compliance with the Biomedical Waste Management Rules, 2016 [50]. In Karad, Satara district, a model for effective biomedical waste management has been established, with 100% segregation, collection, and processing of sanitary and biomedical waste. Conversely, in Kolhapur, residents and activists have raised concerns about the location of the city's biomedical waste treatment plant, citing issues related to pollution and health risks [51]. For the most accurate and up-to-date information on biomedical waste generation in specific cities or districts within Maharashtra for the year 2025, consider the following resources: The MPCB's official website provides access to reports and data on waste management practices and facilities across the state. The CPCB maintains national-level data on biomedical waste, which may include state-wise breakdowns [52].

Municipalities in cities such as Mumbai, Pune, and Nagpur often publish annual reports that detail waste management statistics, including those related to biomedical waste generation and processing.

3.4. Monitoring and treatment of BMW during COVID-19

Not only does COVID-19 have adverse effects on human health, but it also has far-reaching, long-lasting consequences for our ecosystem, affecting every living thing. Even if health is the primary concern right now, many people will die because people are so ignorant about environmental issues in the future. A healthcare facility's plan for handling and disposing of its trash is known as its waste management strategy. Always included are the following: (1) staff duties; (2) healthcare waste classifications and definitions; (3) specific processes for handling healthcare waste; and (5) training for those involved. A few nations have developed alternative techniques since the COVID-19 pandemic became widespread and contagious. All biomedical waste treatment facilities are meant to operate as indicated by the standards and guidelines in the Biomedical Waste Management Rules, 2016, and the Central Pollution Control Board (CPCB). Such healthcare units collect biomedical waste from different health establishments and treat and dispose it under safe waste management conditions. Therefore, following the regulations to minimize these environmental and public health risks from biomedical waste is essential [53], [54], [55], [56].

3.5. Biomedical waste in the post-scenario of COVID-19

The BMW Life Cycle in India encompasses general characterization, quantification, segregation, storage, transportation, and treatment of waste, all of which are integral to the Cradle-to-Grave method that BMW management in India follows (Fig. 4). The public's health and the environment are both endangered by uncontrolled waste.

Environmental expenses are associated with incineration, landfill methane emissions, and the costs of long-distance recycling transportation. Those distances frequently go to the main facilities located across international borders. Accurate data on biomedical waste generation rates, hotspots, and treatment facilities is necessary to modify existing waste facilities during the COVID-19 pandemic to limit atypical medical waste and the viral propagation it causes. Management is concerned about the global surge in BMW manufacturing resulting from COVID-19. The processing centres were overwhelmed with this waste, and the departments inside those centres added food scraps to the pile of infectious COVID-19 waste. The long-suffering worldwide waste management catastrophe has been exacerbated by the rising demand for personal protective equipment (PPE), both medical-grade and non-medical or civil use, because the majority of PPE items are single-use. Traditionally, BMW, along with PPE, is incinerated before a pandemic. What is burned with the current volume of waste also adds to the volume of personal protective equipment (PPE) that the additional 5 billion people are projected to use. Over the next twenty years, the amount of plastic waste is expected to quadruple, and the number of items ending up in the world's oceans is projected to increase fourfold, unless a more effective policy is implemented to address this issue. Specific protocols have been developed by the Central Pollution Control Board to segregate COVID-19 waste, ensuring it is treated and disposed of properly during the pandemic.

These consist of waste produced in isolation wards, as depicted in Fig. 5, which illustrates the process of segregating medical waste. Fig. 4 indicates hazardous waste created as a result of treating patients with COVID-19 at hospitals and healthcare facilities. Table 1 also gives an inventory of potential infectious diseases associated with COVID- 19 healthcare waste, along with a special mention of the requirement for appropriate management to prevent contamination and possible health hazards [57], [58], [59], [60].

Figure 4: COVID-19 waste segregation on-site [61]

Figure 5: Hazardous waste produced as a result of the COVID-19 response [48] Table 1: Primary COVID-19-related healthcare waste kinds [48]

Item	Type of waste	Requires safe handling and treatment
Mask	Infectious	Yes
Gloves	Infectious	Yes
Gown	Infectious	Yes
SARS-CoV-2 Rapid Antigen Test (RAT)	Non-hazardous	Most components are recyclable; a tiny volume of reagent might require safe handling and disposal if dealing with huge quantities of tests
PCR testing cartridge	Chemical	Yes (contains guanidinium thiocyanate)
Vaccine vial	Non-hazardous	No
Vaccine needle	Sharps	Yes (packaging material is recyclable)
Plastic packing and containers	Non-hazardous	No

3.6. Bio-Medical Waste Management in Maharashtra State

The MPCB has started its process to provide permissions for disposing of BMW by HCEs in compliance with the Bio-Medical Waste Management Rules, 2016 [56]. With this formula, we can calculate the rate of change of waste from the pre-COVID era to the post-COVID era:

Rate of change (%) $= \frac{(b-a)}{a} \times 100$

a = BMW generated last year; b = BMW generation in the current year;

Managing BMW in a manner that upholds sustainable development and the eco-accommodating economy. The disposal of any trash represents a danger to the environmental frameworks. BMW is profoundly infectious and potentially infectious to humans, as well as to animals, water, land, and air, if not handled properly [57]. There will be less mischief to people, creatures, and the environment if medical waste is properly generated, treated, and disposed of. One hundred ninety-three individuals on the board of trustees make up the United Nations Gathering,and in September 2015, they laid out 17 SDGS [58], [59]. Objective 3: Good Health and Prosperity, Objective 6: Clean Water and Sanitation, Objective 8: Decent Work and Economic Growth, and Objective 12: Sustainable Consumption and Production are closely linked to healthcare waste management. According to another distributed study, you can sustainably recycle and reuse plastics from medical waste. Additionally, all nations should implement sound medical waste management practices to prevent the devastating accumulation of infectious waste during and after pandemics. The roundabout economy will profit from this, and emissions will decrease as a bonus [60], [61], [62].

4. STUDY AREA

The scope of study of the present comprehensive review is Nasik, a city in the western Indian state of Maharashtra. Considering the severe impacts of the COVID-19 pandemic on the entire region, Nasik, which is diverse in its industrial activities and healthcare facilities, has seen a sharp rise in biomedical waste generation due to increased demand for medical services and equipment during the pandemic period. The study has been designed to compare the pre- and post-pandemic trends in biomedical waste generation using data from healthcare institutions across the region.

This study also employed GIS technology to visualize and analyze the spatial distribution of biomedical waste, aiming to better understand environmental implications and management problems in Nashik. The study period, spanning from May 2020 to March 2025, has enabled a thorough evaluation of the pandemic's impact on reshaping waste management practices and trends in this urban setting [63], [64], [65], [66].

5. RESULTS AND DISCUSSION

5.1. Application-based monitoring with COVID-19

This application is being touted as one of the most critical innovations in ongoing waste management; it tracks waste generation at multiple stages, beginning with generators, handlers, and Common BMW Treatment Facilities (Table 2). It ensures a more comprehensive and streamlined approach to managing biomedical waste throughout its lifecycle.

From the classified information, the 2016 BMW distinguishes between understanding management regulations regarding the capacity to isolate at source and helps in reaching a decision based on the waste classification plan. This has eliminated the time taken during treatment when waste segregation is involved. The application will gather information at the national level, allowing continuous tracking of waste generation, streams, areas of interest, and future required action decisions. Monitoring the amount of waste from various sources has been crucial in identifying interactions. The COVID-19 application has been used as an instrument to track the foundation of the need for additional CBWTFS for safe disposal and treatment [65], [66].

Table 2: Authors and Their Contributions to Waste Management Research

Method	Description	Focus	Research Study	References
Critical Appraisal	Assess India's present biomedical waste handling procedures.	India's Biomedical Waste Management	Draws attention to issues and makes recommendations.	[67]
Index Development	Provides a ranking of nations using the Environmental Performance Index (EPI).	Environmental policy and performance	Evaluates international programs for ecological sustainability.	[68]
Literature Review	Examines the impact of the COVID-19 outbreak on	Impact of Waste Management during COVID-19	Identifies problems with trash management and their solutions.	[69]

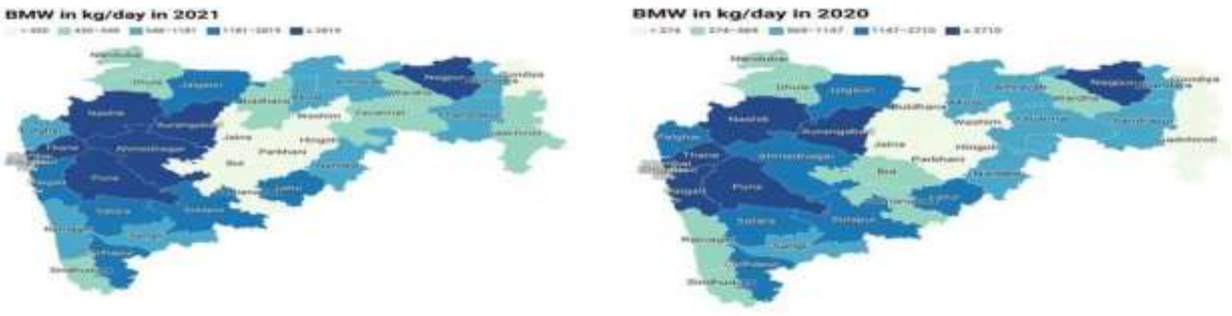
	global waste management systems.			
Literature Review	Highlights the environmental effects of the COVID-19 pandemic.	COVID-19's effects on the environment	Compares and contrasts positive and negative sustainability impacts.	[70]
Report	Explains developments in sustainable personal protective equipment (PPE) production.	Environmentally friendly production techniques	Emphasizes PPE's role in sustainability and waste management.	[71]
Expert Discussion	Examines biomedical waste challenges highlighted during the COVID-19 pandemic.	Challenges in managing biomedical waste	Makes systematic recommendations for improving waste management.	[72]
Narrative Review	Examines sustainable medical waste handling in low-income African countries.	African nations' medical waste management	Discusses challenges and sustainable practices.	[73]
Deep Learning Approach	Use of perceptron model to classify biomedical waste	To improve biomedical waste management by reducing costs and risks associated with manual sorting	Bio-Medical Waste Management: Deep Learning Approach	[74]
Knowledge, Attitude, and Practices (KAP) Study	Survey on knowledge and practices of biomedical waste handlers at AIIMS Mangalagiri regarding COVID-19 waste	Evaluating adherence to best practices in biomedical waste management for COVID-19	Knowledge, attitude and practice of personnel involved in bio-medical waste handling about COVID-19 & its bio-medical waste management	[75]
Literature Review	Review of biomedical waste management practices in the dental field	Inadequate awareness and knowledge of waste management among dental practitioners	Knowledge and Awareness of Biomedical Waste Management in The Field of Dentistry	[76]

Educational Program Evaluation	Assessing the impact of an educational intervention on nurses' knowledge and practices	Enhancing competence in biomedical waste management among nurses	From knowledge to impact: revolutionizing nursing practices in biomedical waste management for sustainable healthcare excellence	[77]
Emerging Green	Evaluation of green	Promoting environmentally	Emerging Green Technologies for Bio-	[78]
Technologies Review	technologies for biomedical waste treatment	friendly solutions for waste management	medical Waste Treatment and Management: A Systematic Approach	
Bioremediation Review	Review of bioremediation techniques for detoxifying biomedical waste	Sustainable, cost-effective methods for handling non-biodegradable and toxic biomedical waste	Applications of bioremediation in biomedical waste management: current and future prospects	[79]
Waste Management Review	Overview of biomedical waste and its environmental effects	The impact of waste on human health and the environment	Biomedical waste management and their effects on the Environment: A review	[80]

5.2. COVID-19 BMW generated in Nashik

With 17% of India's total COVID-19 biomedical waste, the pandemic had a significant impact on Maharashtra. As India's second most populous state, it is crucial to investigate the districts' BMW, with Nashik as the case study. Nashik was identified as a district with modest waste creation in 2020, with daily biomedical waste production ranging from 569 to 1,174 kg. The western part of Maharashtra, which includes the districts of Thane, Mumbai, Pune, Raigad, Nashik, and Nagpur, provided the bulk of the garbage. Nashik joined the ranks of the highest waste- generating cities in 2021, with a daily production of more than 28, 19 kg, indicating a considerable increase in garbage creation patterns.

According to the quantile approach, Nashik, Mumbai, Thane, Aurangabad, and Nagpur are currently among the regions with extraordinarily high garbage generation. The neighboring regions' trash output levels were low, ranging from 548 to 1,181 kg/day. On the other hand, Hingoli, Jalna, Parbhani, and Washim were among the regions that maintained a consistently low BMW production of less than 450 kg per day. As the number of BMWs manufactured in Nashik continues to rise, it becomes increasingly clear that effective waste management strategies are crucial for addressing the surge in biological waste assciated with the epidemic (Fig. 6)



According to the Maharashtra Pollution Control Board (MPCB) Bio-Medical Waste Annual Report for 2022, Nashik district generated approximately 520 kg of biomedical waste per day. This figure ranks Nashik among the districts in Maharashtra with moderate levels of biomedical waste generation. The report categorizes districts into three groups based on daily waste generation [82]: Very High (> 2,710 kg/day), including Mumbai Metropolitan Region, Pune, Thane, Raigad, Nashik, and Nagpur. Moderate (569–1174 kg/day): Surrounding districts to the high waste-generating regions [83]. Very Low (<374 kg/day): Central and Vidarbha regions of Maharashtra [84]. Additionally, the MPCB Bio-Medical Waste Annual Report for 2023 provides district-wise data on the generation of biomedical waste. While the specific figure for Nashik is not detailed in the available summary, the report includes information on various districts [85] [86].

6. CONCLUSION

The study demonstrates the significant impact of the COVID-19 pandemic on the volume of biological waste generated in Nashik, Maharashtra. It illustrates the significant increase in waste production during the crisis. Prior to the pandemic, Nashik's biomedical waste generation was relatively low, but it increased significantly with the surge in demand for medical equipment and services. This increase makes it significantly more challenging to manage waste in the area, including sorting, treating, and disposing of it. The study also indicates that infrastructure, rule compliance and public knowledge problems all make the proper disposal of biological waste difficult. The findings also clearly indicate that the surge in bio-medical waste has overwhelmed existing waste treatment plants, further aggravating threats to the environment and public health. Technologies such as app-based monitoring, improved waste handling, and stricter enforcement of rules can go a long way in revamping the way biomedical waste is handled and disposed of. In addition, health facilities should implement quality public education and ongoing staff training to minimize the risk of biological waste. The environment needs to be protected, and growth should be sustainable. Enhancing waste treatment, ensuring proper separation, and applying new technologies are the ways to achieve this. To better prepare for managing biomedical waste in the future, cities like Nashik and other areas with similar health infrastructure should invest in upgrading their infrastructure, building additional treatment facilities, and enacting strict regulations. This breed of approach will be required to protect the environment, public health, and ensure that rules are adhered to. This will produce a better and more sustainable future.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper the authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Credit authorship contribution statement:

Rupali Patil: Conceptualization, data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration. Validation, Editing, Conceptualization, Validation, Editing, Methodology, Investigation, Resources, Investigation

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