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REVIEW ARTICLE

Accumulation of biomedical waste during the COVID-19 pandemic: concerns and strategies for effective treatment

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Abstract

This study deals with the pollution impact of biomedical waste (BMW) generation due to the COVID-19 pandemic at both the global and national levels. This discussion is important in light of clear scientific evidence that, apart from the airborne transmission of the disease, the virus also survives on different surfaces and poses the risk of infection. Moreover, an investigation is conducted on BMW generation in tons/day in India during the COVID-19 period, with implications for future projection. Additionally, a pioneering study was conducted to estimate the usage of facemasks during the COVID-19 pandemic in India. This paper also provides a feasible solution, by adopting a modern perspective, towards managing BMW generated in the context of SARS-CoV-2 at isolation wards and crematoriums. Strategical approaches have been suggested for segregating and safely disposing BMW. The latest availability of disposal facilities is discussed based on source data provided by the Central Pollution Control Board (CPCB), India. Among the many disposal methods, incineration technologies are examined in depth. The impact of existing incineration technology on the environment and human health has been extensively studied. This study suggests strategies for controlling BMW generation during the COVID-19 pandemic.

Keywords Crematorium · Disposal practices · Facemask disposal · Incineration · Personal protective equipment · SARS-CoV-2 · Waste management

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Introduction

Waste generated over the course of medical diagnosis, treatment, and research is considered biomedical waste (BMW). The proper handling of BMW is critical and has remained a challenging problem over the past few decades. According to the World Health Organization (WHO), of the total waste generated by healthcare activities, approximately 85% is general and non-hazardous waste, while the remaining 15% includes clinical solid waste, expired vaccines, unlabeled products, medical instruments, and organic fluids that are considered infectious, toxic, and hazardous to humans and the environment (WHO 2018). Therefore, care and caution must be taken to ensure that these wastes are properly managed and safely segregated. A large portion of these wastes worldwide are managed using technologies such as wastewater treatment, land disposal, gasification, and incineration. A best available technology (BAT) survey for identifying safe and sustainable BMW treatment options and management methodologies was conducted in 24 countries in the Western Pacific area in 2012. Japan and the Republic of

Korea were the only two countries that effectively managed their BMW. The evaluation was conducted by assessing five major management areas: training, policy, regulatory framework, technologies implemented, and financial resources (Datta et al. 2018). Canada is a pioneer in this field, and it has centralized provincial facilities for BMW sterilization (Walkinshaw 2011).

Several decades ago, Indian employees working with BMW were unaware of the need for suitable protective equipment on the job. For instance, medical syringes were reused without proper sterilization until 2009 (Salkin and Kennedy 2004). During this period, approximately 240 people in Gujarat were affected by hepatitis B owing to the reuse of unsterilized syringes (Seetharam 2009). International clinical epidemiology imposed the existing BMW practices in 20 Indian states during 2002—2004 based on detailed questionnaires that were used to sub-classify the standards. An earlier research study found that 82%, 60%, and 54.2% of primary, secondary, and tertiary healthcare centers, respectively, were in the red category, indicating a critical need for immediate measures to stringently enforce an efficient BMW management system in the country to curb the spread of infections (Arora et al. 2014).

BMW generation has increased at an abnormal rate recently due to the spread of COVID-19, an infectious virus whose origin has been traced to a localized seafood marketplace in Wuhan, China; the virus was later referred as SARS-CoV-2 by the WHO on January 12, 2020 (Dharmaraj et al. 2021). Due to the global transmission and worldwide impact of the coronavirus, the WHO declared it a pandemic on March 11, 2020. By September 16, 2021, SARS-CoV-2 had reportedly spread across 237 republics with 226,236,577 confirmed cases leading to 4,654,548 deaths (WHO 2021a). The infection growth rate of COVID-19 is greater than those of SARS and MERS, with a short gestation time of 24 h (Zhang et al. 2020). The primary source of COVID-19 transmission is inhalation of respiratory droplets from close contact with an infected person (Kitajima et al. 2020). COVID-19 can also be transmitted in other ways: it is shed from the faces of infected patients displaying acute symptoms and can be contracted from asymptomatic persons and treated patients without any signs (Thakur et al. 2021).

This situation has resulted in many healthy people becoming infected, requiring medical treatment, and in certain severe cases requiring hospital admission. The essential protective equipment used by healthcare professionals for treating sick patients and mandatory precautionary safety measures such as facial masks and hand gloves have led to a substantial increase in BMW accumulation worldwide. In China, nearly 240 tons of medical waste is discarded daily; prior to the pandemic, this volume was 40 tons on normal days (Hossain et al. 2020). Even before the pandemic, BMW generation in India had increased from 559 to 613 tons per day between 2017 and 2019 (CSE India 2021), and in the course of battling the pandemic, the country currently generates around 850 tons of BMW per day (Chand et al. 2021). The major repercussion of this steadily increasing BMW generation is its effect on the environment. Thousands of sanitation workers, rag pickers, and garbage segregators were unaware of the importance of PPE, which may have resulted in the loss of many lives. The generation of BMW at the end of COVID's first and second waves continued to increase due to careless disposal of surgical masks, gloves, personal protective equipment (PPE) suits, etc., leading to many people being affected by SARS-CoV-2. The Indian government has recommended that all healthy people aged 18 years and above must receive a vaccination; as of September 14, 2021, 56,345,040 people had been successfully vaccinated (WHO 2021b). The syringes and vials used during vaccinations were added to the growing pile of BMW. To manage the enormous amount of waste produced daily during the pandemic, a proper BMW disposal method must be adopted. Despite the imposed strict rules, regulations, and specified guidelines imposed by the Indian government for maintaining a clean ecosystem, these regulatory policies are largely ineffective for the safe disposal of BMW without the deployment of appropriate technological solutions. To achieve this, most Indian states have adopted the incineration technique because it requires of less space, energy, and cost.

To help the society and to address the identified information gap, the key objective of this assessment study is to summarize the current knowledge on approaches for treating BMW, to support further research needs, and to resolve obstructions to the enactment of various treatment technologies. The impact of the coronavirus on the BMW generation is discussed in detail to elucidate the scientific background. Various remedial approaches for efficient BMW (Thind et al. 2021) management are discussed along with their advantages and disadvantages. In light of the increasing number of COVID-19 cases and the danger of an impending catastrophe of the third wave from new variants and mutations of the virus, building greater awareness can help garner the attention of the scientific community and society to the critical need for effective BMW management in India.

Persistence of coronavirus variants on different surfaces

Early clinical research records indicated the possibility of the virus spreading through zoonotic transmission. Subsequent reanalysis of the epidemic data showed that it first spread via human-to-human transmission in December 2019 (Nishiura et al. 2020). The mode of transmission of the coronavirus is through respiratory droplets from the sneeze or cough of an infected person that lingers over time on different surfaces (Suman et al. 2020); this is called infection decay. Figure 1 depicts the decay time of SARS-CoV-2 on different materials, most of which are commonly BMW items. Alcohol-based disinfectants, called sanitizers, can significantly reduce the survival and decay times of different coronavirus variants (Gold et al. 2018).

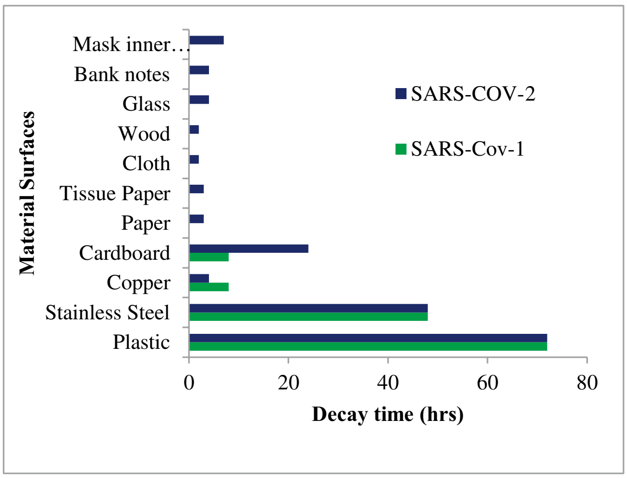

Fig. 1 Decay time of the coronavirus (Suman et al. 2020; Tripathi et al. 2020) (in hours)

Potential BMW generation from leading COVID-19 cases

The present article discusses the global situation as well as the Indian scenario of the impact of SARS-CoV-2 on BMW generation and suggests measures for its effective management through various strategies using systematic approaches. Additionally, this paper covers the possibility of BMW leading to more COVID-19 cases, current perspectives on BMW management, ongoing BMW management strategies, global behavior patterns relating to waste collection and disposal, challenges in BMW management, environmental effects, and potential sustainability strategies. Figure 2 illustrates a sequential overview of healthcare solid waste management during the COVID-19 pandemic. BMW generated due to COVID-19 were divided into five categories. They were processed for waste management with liquid waste using the oxidation pond method, cotton cloth, syringe, PPE, masks in treatment and disposal methods, dead bodies, and infected tissues in cremation or burial.

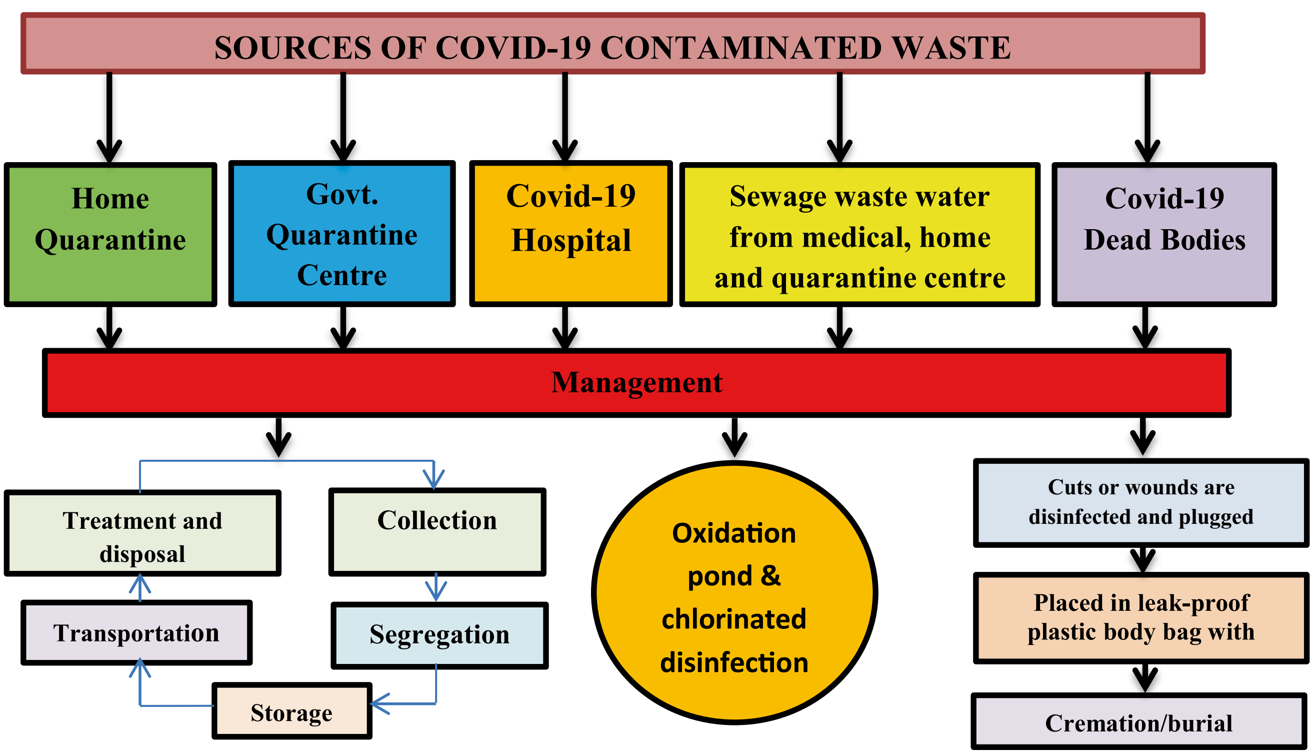

Fig. 2 Overview of healthcare solid waste management during the COVID-19 pandemic (Behera 2021)

Global scenario

The impact of COVID-19 has increased the global market for personal protective equipment (PPE) from $40 billion to $58 billion (Singh 2020). The BMW produced in different countries (tons/day) is projected in Figure 3, based on data from July 31, 2020. The collection and disposal of BMW between March 22 and April 12, 2020, in Regina, Canada, increased nearly fourfold from 355.5 to 1222.4 tons per week (Richter et al. 2021). Similarly, the State Council of China found that approximately 468.9 tons of medical waste are now produced daily (Peng et al. 2020). In Indonesia, it was noted that the produced medical waste reached 12,740 tons in the first 60 days after the first COVID-19 case was reported. Sangkham studied the total medical waste generation by all countries and identified that the highest quantities of medical waste were produced by India, Iran, Pakistan, Saudi Arabia, Bangladesh, and Turkey (Sangkham 2020).

Indian scenario

Owing to the increased number of treatment centers during the initial period of the pandemic, BMW generation correspondingly increased. As of May 31, 2020, CPCB estimated that India would produce 710 metric tons (MT) of BMW per day. Approximately 101 MT/day of the projected amount was from COVID treatment hospitals, quarantine wards, sample collection centers, and testing laboratories. The total BMW produced by private and government hospitals before the pandemic was 500 g/bed per day. This figure increased from 2.5–4 kg/day/bed (Singh et al. 2020) because of COVID-19. Meticulous segregation of BMW based on the intensity of patient infection is among the best ways to restrict further COVID-19 cases. Fig. 4 depicts data on BMW generation (CPCB 2021) and the increasing case history in India (WHO 2021a), which indicates that the

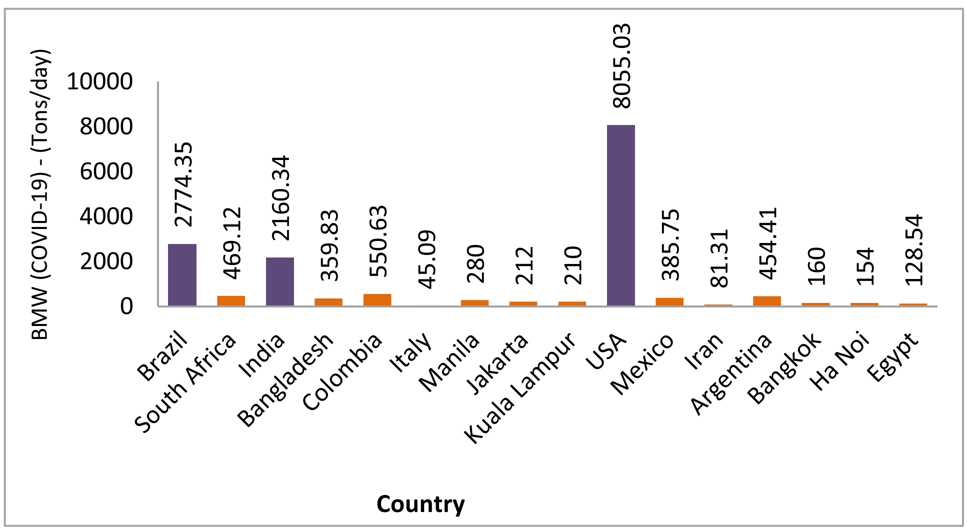

Fig. 3 COVID-19 BMW produced by different countries (Sangkham 2020)

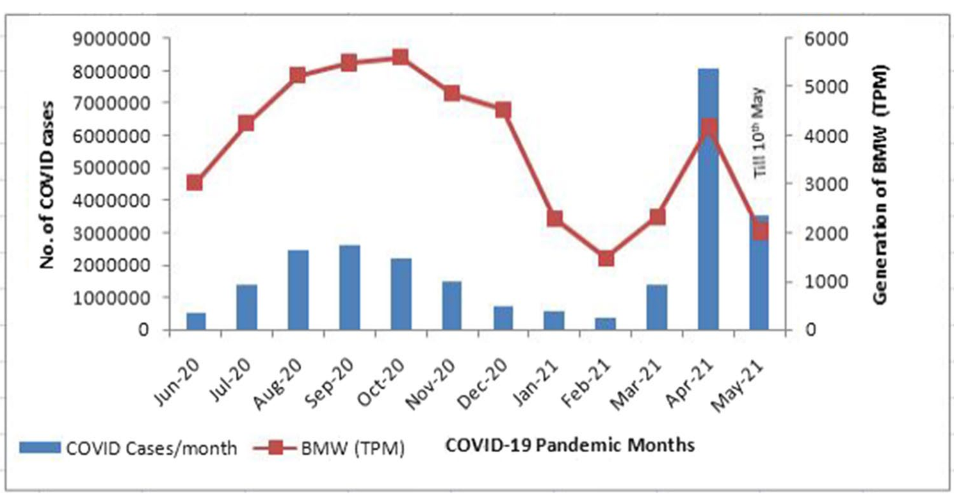

Fig. 4 Variation in BMW generation corresponds to COVID-19 cases

rate BMW generation depends on the number of COVID cases in India.

Indian-States Scenario

The entire nation has focused on battling the COVID-19 pandemic, with many people struggling to earn enough for their basic livelihood. All citizens have started using precautionary measures, such as masks, PPE kits, shields, gloves, vaccines, social distancing, and self-quarantining when ill. The CPCB released statewide BMW details from January to May 2021 (CPCB 2016), as shown in Fig. 5.

Due to a market increase in the use of single-use medical/clinical protective wear as a precautionary measure, there has been a substantial increase in the quantity of BMW generated on a day-to-day basis.

Estimation of facemask usage in India during the COVID-19 pandemic

The discarded waste of masks and gloves contaminated with blood, bodily fluids, tissues, organs, and sharp objects from clinical treatment is known as BMW. If managed and disposed without care, these items are likely to pollute the environment and cause health issues. Everyone has started using facemasks as a precautionary measure against the coronavirus, particularly after a governmental advisory about its importance. To develop an efficient waste management system during the pandemic, facemask usage in different Indian states was estimated in an earlier study. Information regarding confirmed COVID-19 cases in India was collected from the official website of myGovIndia and population statistics were collected from UIDAI. The quantity of daily facemask usage was estimated using Eq. (1).

$$D_n = P \times U_p \times F_R \times F_d \quad (1)$$

This study provides a reliable forecast of the country's facemask usage during the COVID-19 pandemic. Figure 6 shows that 323,980,624 facemasks were expected to be used in India (Sangkham 2020). From the graph, it can be inferred that the rate of increase in mask usage depends on the number of COVID-19 patients affected in the respective states (as per August 2021, data sourced from the World Meter 2021). Maharashtra, Uttar Pradesh, Tamil Nadu, and West Bengal were the four Indian states with the highest numbers of COVID-19 cases.

Modern BMW management in the context of SARS-CoV-2

A steady increase in the number of people become sick after COVID-19 infection has affected the living standards of people worldwide. To control the rampant spread of infection, India has refurbished 238,170 healthcare centers, of which 87,267 are equipped with BMW separation (Chand et al. 2021) facilities. The CPCB has revised the recommendations for the treatment, handling, and dumping of BMW produced for the duration of the diagnosis/isolation/treatment of COVID-19 patients (CPCB 2020) based on the specific segregation and disposal facilities that were drafted under BMW Management Rules, 2016.

Handling waste from COVID-19 isolation wards

The following BMW handling processes have been enacted in COVID-19 wards of India:

- Separate color bins with foot-operated lids to maintain proper waste segregation.
- Use of double-layered bags for BMW collection.
- Collection and storage of BMW before it reaches the staff of common biomedical waste treatment facilities (CBMWTF).

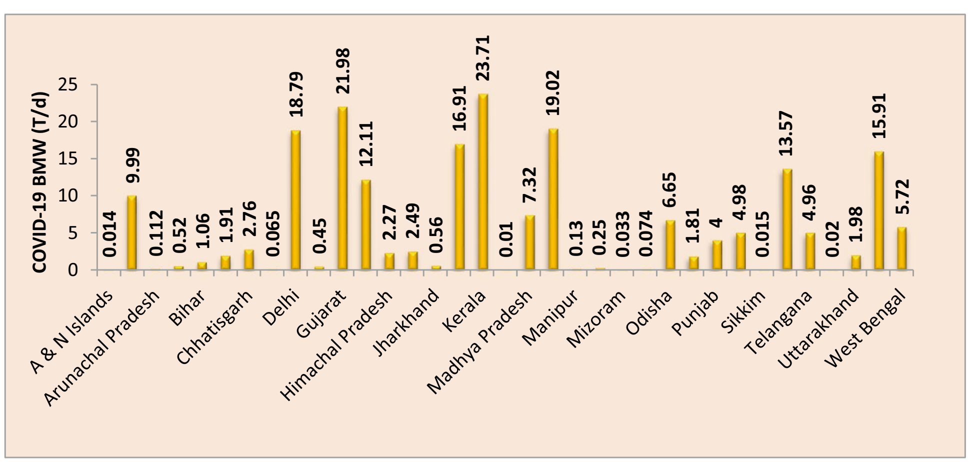

Fig. 5 Statewide BMW generation (tons/day) during the COVID-19 pandemic

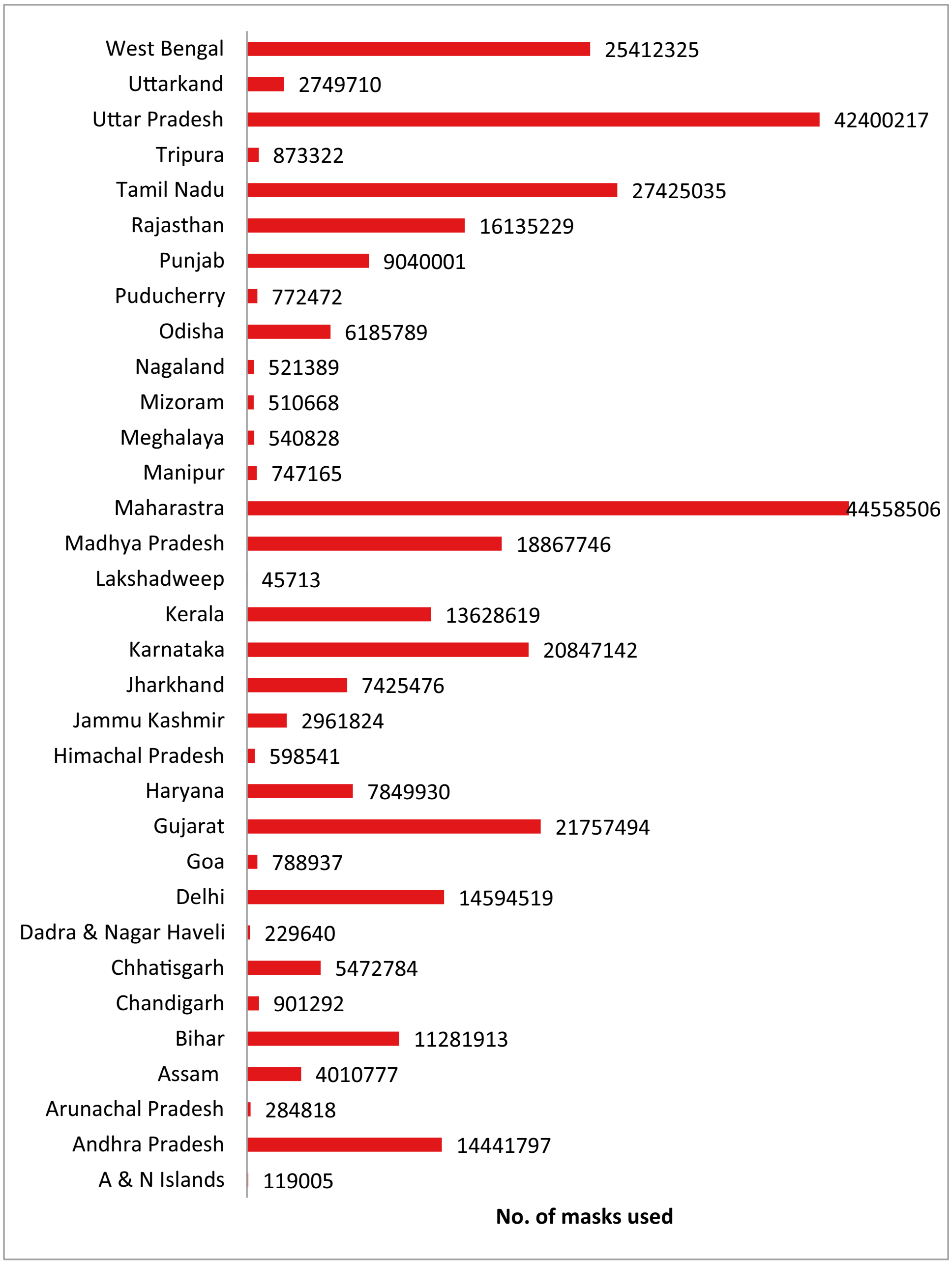

Fig. 6 Estimated daily facemask usage in India corresponding to confirmed COVID-19 cases

- Labeling segregated COVID-19 BMW bags as "COVID-19 Waste."
- Use of dedicated trolleys and bins, treated with disinfectant after every use.
- The feces of COVID-19 patients are treated as BMW and collected in a diaper before disposal in the yellow bag.

Handling and disposal of used PPE

- Waste masks and gloves should be kept in yellow bags for a minimum of 72 h before disposal to avoid the risk of virus transmission.
- Discarded PPE from the public should be stored in a separate bin for 3 days before their disposal as dry general solid waste after shredding.
- At material recovery facilities, discarded plastic PPE should be shredded and sent to authorized plastic waste recyclers or converted into refuse-derived fuel (RDF) for co-processing or energy recovery in road making.

Handling of BMW in crematoriums

As of September 16, 2021, the rapid spread of COVID-19 has resulted in 4,654,548 deaths globally, with 443,928 of those in India (Worldometer 2021). There are no restrictions on the disposal of incineration ash that remains after the cremation of the dead bodies of COVID-19 patients (WHO 2020a). However, regulations have been enacted for BMW that accumulates at the crematorium. The higher potential for COVID-19 transmission can be checked and controlled by proper handling and management of the generated BMW. The BMW generated in the crematorium must be collected in a separate bin with a yellow bag; it must remain untouched for 72 h and then should be handed over to authorized waste pickers. The waste must then be disposed as per the provisions given under the sewage waste management rules, 2016 and BMW Management Rules, 2016 (MOEF and CC 2016).

Guidelines for handling facial mask

According to the guidelines provided by the All-India Institutes of Medical Sciences (AIIMS), N95 masks should be decontaminated with 11% hydrogen peroxide vapors (HPV), whereas 70% ethanol and 0.5% sodium hypochlorite solution should be used to decontaminate face shields and goggles (AIIMS 2020). Based on the results of the HPV treatment formulated by Fischer, this method exhibited the best results in rapid inactivation of SARS-CoV-2. Additionally, dry heating at 70 °C can kill the virus. Decontamination with alcohol can degrade the integrity of N95 masks and is hence not recommended. The study suggested that respirators can be decontaminated a maximum of three times by UV and HPV treatments and twice by dry heat (Fischer et al. 2020).

Potential BMW management strategies during COVID-19 pandemic

Due care and caution must be exercised in BMW disposal, as it must be collected according to governmental regulations and medical care facility (MCF) rules. Many countries have adopted the best possible waste management strategies based on available resources, capacity, and commitment.

Segregation of BMW

The healthcare solid waste classification criteria set by the WHO covers the separation of different types of waste according to classification after its immediate usage. Segregation involves separating waste into appropriate containers with color codes, as shown in Fig. 7. Color coding is employed to easily identify different waste types. Red bins are commonly used to dispose of tubing, bottle sets, catheters, urine, bags, and vacutainers. Yellow bins represent anthropogenic waste of humans, anatomical waste of animals, solid waste, and solid and liquid chemical waste. White bins are used for metallic sharp waste, such as needles, scalpels, blades, and syringes with fixed needles. Blue

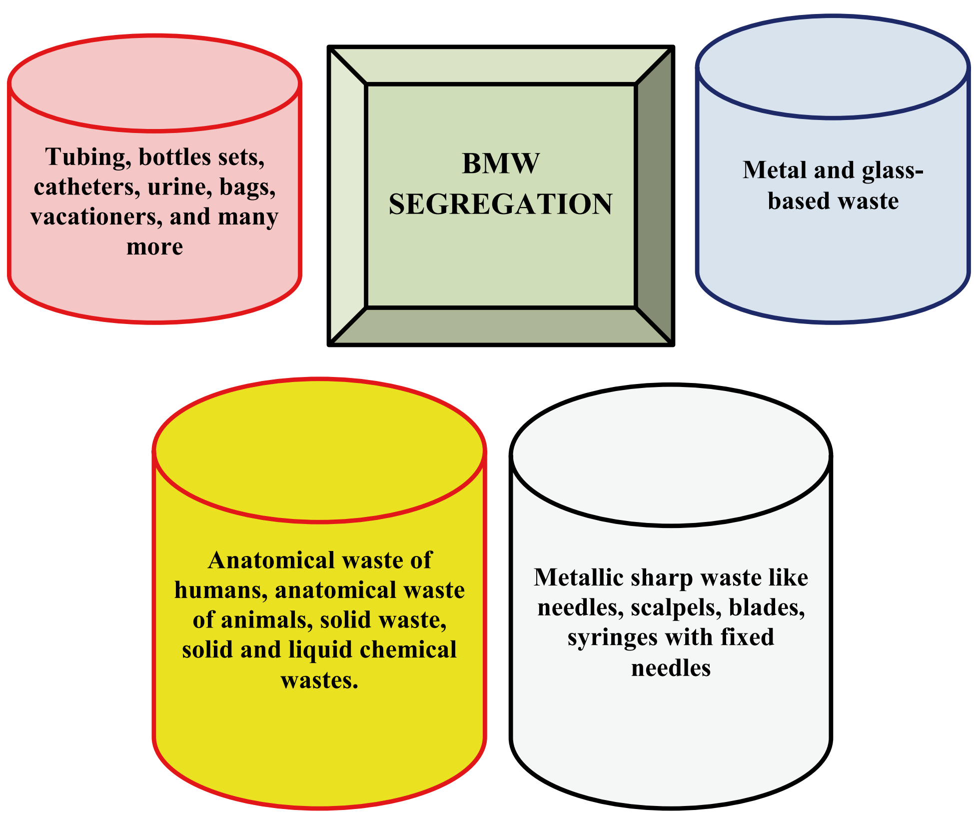

Fig. 7 Segregation of BMW in respective color-coded containers

bins represent metal- and glass-based waste. These waste containers should be rigid, leak-proof, unbreakable, and puncture resistant (Kothari et al. 2021).

Transportation and temporary storage of BMW

Medical waste transport of is one of the most important processes in BMW management and has evolved scientifically over time. There are several restrictions during transportation. Initially, psychological stress due to anatomical waste handling during segregation was a major issue. Additionally, needlestick injuries lead to blood-borne infections. Transportation containers must be marked with a biohazard emblem and locked properly before transit. For temporary storage, hospital waste storage facilities should be approximately 500 m away from the patient care sections. The storage room should be surrounded by an iron-grilled fence that is kept secure at all times and opened only when necessary. Biohazard signs must be clearly posted on the gate. Two waste treatment rooms, for an autoclave and a shredder, should be established within health care facilities. During the segregation, transportation, treatment, and disposal of health care waste, staff are regularly instructed and encouraged to use safe health care waste management techniques (Kumar et al. 2015).

Various BMW disposal practices

Clinical biomedical waste is classified into general and perilous types. General waste does not require extra care, whereas perilous waste must be managed carefully during disposal. Commonly used methods of disposal are drains, land disposal, plasma gasification, and incineration. Table 1 lists the disposal methods for generated BMW. Some of these methods are suitable for use within healthcare facilities (Ghada and Bulent 2021; Reddy et al. 2021). Sterilization can be performed in a small area allocated specifically for BMW in hospitals, as shown in Table 2.

Indian waste management scenario

According to the information provided by the State Pollution Control Boards (SPCBs), 101 T/d of COVID-19 BMW were produced from 2,907 hospitals, 20,707 quarantine centers, 1,539 sample collection centers, and 264 testing laboratories in the year 2020. The overall capacity of all treatment plants in India was 710 T/d with 195 centers. CPCB framed the compliance report, as projected in Table 3 (CPCB 2020).

Table 1 Comparison of different methods for BMW disposal

Parameters	**Sewage/drain** (Biswal 2013; Ethica et al. 2018)	**Land disposal** (Babu et al. 2009)	**Plasma gasification** (Messerle et al. 2018; Paulino et al. 2022)	**Incineration** (Rajor et al. 2012; Kaur et al. 2019)
Availability	Common and assessable	Common and oldest	Difficult due to technical impracticalities	Cheap and affordable
Cost	Moderate	Low	High	Efficient
Feed for treatment	Liquid BMW	BMW	Municipal, solid, biomedical, and hazardous wastes	All types of wastes apart from sharp items
Need for pre-treatment	Yes	No	No	No
Types of pollution contributed	Water contamination and GHG	Air pollution, and water contamination	Air pollution	Air pollution
By-product	Semi-solid waste or slurry	Ash when burned	Slag and reduced metals, Producer Gas	Incineration ash (another type of BMW), heavy metals

Table 2 Different sterilization techniques for killing germs/pathogens

Autoclaving	Low-heat warm cycle wherein steam directly contacts with biomedical wastes to sterilize the waste (Armstrong and Reinhardt 2010)
Microwave Light	The warm impact of electromagnetic radiation ranges between the frequencies of 300 and 300,000 MHz, resulting in microbial inactivation (Praveen Mathur et al. 2012)
Low warmth treatment frameworks	This innovative treatment purifies waste by destroying microorganisms (Pasupathi et al. 2011)
Synthetic Techniques	Utilized regularly in medical care to kill microorganisms on clinical gear and all floors and dividers (Patil and Bohara 2020)

Table 3 Statewide generation of COVID-19 BMW and disposal facilities

S.No	Name of State/UT	COVID-19 BMW (in TPD)	Facility Details					Adequacy of an existing treatment facility
			No. of CBWTFs engaged	Captive facilities		Deep burial pits		
				Y	N	Y	N	
1	A & N Islands	0.014	0					Adequate with captive facilities.
2	Andhra Pradesh	5.516	11					Adequate.
3	Arunachal Pradesh	0.112	0					Depends on burial pits.
4	Assam	0.946	1					The capacity of the Common Biomedical Waste Treatment Facility (CBWTF) is not adequate and one facility cannot cater to the needs of the entire state. Need to depend on the captive facilities and burial pits.
5	Bihar	0.228	4					80% of the incinerator capacity is utilized. Need to ensure proper segregation technique.
6	Chandigarh	0.995	1					Adequate
7	Chhattisgarh	0.373	2					The adequate capacity of CBWTFs. Details of more disposal options are not provided.
8	Dadra & Nagar Haveli	0.015	1					Adequate. Waste is being disposed of through CBWTF at Surat, Gujarat.
9	Delhi	11.114	2					70% of the existing capacities of two incinerators are utilized. Need to ensure proper segregation.
10	Goa	0.027	0					No CBWTF. Need to depend on captive facilities and burial pits.
11	Gujarat	11.693	20					Adequate.
12	Haryana	2.511	11					Adequate.
13	Himachal Pradesh	0.127	2					Adequate capacity with incinerators. two CBWTFs may not be adequate to cover the entire state.
14	Jammu and Kashmir	0.357	2					Two CBWTFs may not be adequate to cover the entire state. Need to depend on captive facilities and burial pits.
15	Jharkhand		2					Compiled information was not available and hence adequacy could not be assessed.
16	Karnataka	2.8	25					Adequate.
17	Kerala	4.71	1					All COVID biomedical waste was sent to CBWTF. The capacity of CBWTF is not adequate for the total BMW. Hence captive facilities need to be operated.
18	Lakshadweep	0.01	2					Adequate. May use 2 captive incinerators in 2 islands and deep burial pits in the rest of the islands.
19	Madhya Pradesh	7.486	11					Adequate.
20	Maharashtra	17.494	29					Adequate. Standby arrangement is made with Treatment, Storage, and Disposal Facilities (TSDFs) in Mumbai, Pune, and Nagpur cities.
21	Manipur	0.171	1					Adequate. However, a single facility may not cater to the entire state.
22	Meghalaya	0.17	1					Adequate information is not available. The existing incinerator cannot dispose of the entire waste generated from the state.
23	Mizoram	0.14	0					Adequate information is not available.
24	Nagaland	0.12	0					Adequate information is not available.
25	Odisha	1.062	5					79% of the common incinerator's capacity is utilized. Need to ensure the proper segregation of waste.
26	Puducherry	0.621	2					Adequate.
27	Punjab	1.6	5					Adequate.
28	Rajasthan	5..9	8					88% of the common incinerator's capacity is utilized. Need to ensure proper segregation and identify the alternate facilities
29	Sikkim	0.2	0					Adequate information is not available.
30	Tamil Nadu	10.41	8					91% of incinerator capacity is utilized. Eleven Centres need to ensure proper segregation and identify alternate incinerators/disposal options
31	Telan	0.41	11					Adequate
32	Tripura	0..015	1					71% of incinerator capacity is utilized
33	Uttar Pradesh	0.53	2					92% of Incinerator capacity is utilized. Only 2 incinerators may not be adequate to cater entire state area. Need to depend on deep burial disposal.
34	Uttarakhand	7	18					Adequate.
35	West Bengal	6.5	6					Adequate.
Total		101	195					

Potential disposal of BMW during COVID-19

Of all the techniques, incineration emerged as among the most efficient and reliable methods to safely dispose of tons of BMW. The incineration method has many benefits: it is affordable, easy to manage, operate, maintain, and can be easily transported. Using the incineration process, waste is treated to reduce the volume by 90% and the weight by 70%, which is important considering the quantity of BMW requiring rapid disposal (Jaber et al. 2021). The main advantage of the incineration method is the release of heavy metals such as Hg, Pb, Cd, Cr, Cu, Zn, and Ni, which are used in chemical industries (Linak and Wendt 1993), as by-products during the combustion processes (Liu et al. 2012). This study intends to highlight the existing BMW incineration plant capacity, particularly during the COVID-19 pandemic.

Quantitative and qualitative BMW disposal using incineration and thermal technologies

The hazardous waste generated during the pandemic was mainly comprised of large PPE kits and other single-use medical care equipment. A monthly increase of 40% in the production of PPE kits was reported due to the spread of COVID-19 (WHO 2020b). As shown in Fig. 4, the waste segregated in the BMW yellow category (Y-BMW) is a predominant category of waste that can be disposed of using incineration technologies. Alternatively, plasma gasification at 1050 °C was used for Y-BMW. Red (R-BMW), white (W-BMW), and blue (B-BMW) categories of BMW are disposed of with dry sterilization and autoclaving at minimum temperatures (Dehal et al. 2021). The sudden increase in waste generation owing to COVID-19 has challenged waste management systems worldwide. During the peak of the virus in China, waste generation increased six-fold in tons per day, whereas in the USA, it increased from 5 to 300 MT/y; facemasks alone resulted in 66,000 tons of Y-BMW. From Jan 20, 2020, to May 30, 2020, the Republic of Korea generated approximately 2000 T of Y-BMW. The proportion of Y-BMW of the total BMW generated by seven states including Delhi, Haryana, Rajasthan, Madhya Pradesh, Maharashtra, Mizoram, and Uttarakhand in India was estimated at 50.44% by the CPCB report (Thind et al. 2021). Incineration is the preferred method for Y-BMW disposal in India.

Impact of BMW on the environment and human health

The untreated and illegal disposal of biomedical waste affects human health and the environment. Anurah et al. conducted a study on the negative effects of BMW in humans and concluded that generated BMW is a source of numerous communicable and non-communicable human health problems (Deepak et al. 2021). Generally, BMW creates a difficult condition not only for human health but also for ecology as a whole. According to reporters, the pandemic-related growth in BMW, particularly PPE, has resulted in massive waste generation. This waste has a significant impact on biosphere components such as air, water, and soil (Kothari et al. 2021). This impact is particularly related to disposal methods; clinical waste incinerators release toxins such as particulate matter (PM), fly ash debris, and heavy metals such as arsenic, chromium, copper, mercury, and lead (Valerio 2010). These emissions include corrosive gases such as hydrogen chloride, hydrogen fluoride, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulates. Scientists from different nations have conducted a variety of tests encompassing the diagnosis, disinfecting, cleaning, testing, and incineration processes and have observed the release of highly poisonous gases that can cause serious diseases such as cancer (WHO 2016), lead to reproductive and developmental problems, and damage the immune system. They also observed that these components are toxic, flammable, highly reactive, and genotoxic (Sarkodie and Owusu 2021). Continuous exposure to and inhalation of harmful gases can result in cancer. The occurrence of carcinogenic and non-carcinogenic health risks associated with the exposure of adults and children in India resulting from Y-BMW incineration of was studied by Singh (Thind et al. 2021).

BMW control methods during COVID-19

The onslaught of the COVID-19 pandemic caused an unprecedented increase in the composition and volume of waste products; this has created a critical situation in different states in which existing incinerators are operating at upwards of 70% their capacities. The following are suggestions for enhancing BMW management in developing countries such as India.

- Ensure effective utilization of color-coded bins for collection and disposal (Datta et al. 2018).
- Improve the current bio-waste management policies, plans, and guidelines.
- Create a universal strategic plan to segregate, collect, store, transport, and dispose of the generated waste.
- Expand treatment capacity, investments in health infrastructure, and hiring of qualified health workers (Deepak et al. 2021).
- Conduct occupational health and safety assessments.
- Manage household infectious waste.

- Install proper incinerators and related infrastructure, with special emphasis on mobile incinerators.
- Investigate the environmental fate, behavior, degradability, and consequences of used PPE, plastic additives, and pathogen transfer potential.
- Analyze technical, managerial, and sustainability descriptions for disposal effects (Datta et al. 2018).
- Include the environmental implications of BMW in educational curriculum to increase awareness among future generations (Dehal et al. 2021).

Policymakers and governmental bodies should come forward to revamp existing policies and guidelines by considering the present pandemic situation. A regional network must be established and baselines must be framed for knowledge sharing and concentrated BMW management. Such actions will immensely help developing countries like India to deal not only with the current situation but also to equip themselves to tackle the BMW challenges in future upcoming pandemics (Shammi et al. 2021).

Conclusions

The implementation of a systematically planned and smoothly functioning BMW management system that oversees collection, handling, segregation, storage, processing, disinfection, and disposal facilities will ensure that there are no adverse impacts on society, the ecosystem, or the environment. BMW treatment plays a predominant role in maintaining a clean and healthy society that could be affected by the illegal dumping of potentially infectious and hazardous waste in open public spaces. The pandemic has shaken the entire world, including developed countries, which continue to struggle to manage proper BMW disposal. Most developing countries, including India, do not utilize the full potential of disposal techniques, particularly incinerators. Technical and operational improvement of incineration technologies is necessary for the sustainable management of BMW generated from COVID-19 treatment in the country. BMW generation is continuously increasing because of an increase in the number of COVID-19 cases. Therefore, disposable masks, gloves, and PPE kits are mandatory to safeguard against the contagious virus. The proper disposal of this medical waste is a significant problem. Safe and sustainable management of BMW generated by the healthcare system in compliance with prevailing laws is, therefore, an urgent need. Hence, incinerators play indispensable roles in safeguarding human lives and protecting the environment by sustainably managing BMW. Incineration is an appropriate disposal method adopted for the easy processing of Y-BMW, which forms a significant part of the total BMW. Many biotech industries and healthcare centers lack the technology and know-how to correctly segregate waste before incineration; proper segregation of BMW and modern biomedical waste incineration units must be installed on-site in all medical centers. The government must take steps to prevent the risk of open disposal and improper dumping of toxic biomedical waste through continuous monitoring and active regulatory bodies. Strict laws, policies, and regulations must be framed to penalize and control the unsafe disposal of hazardous BMW in public areas. Frequent awareness programs, education, and proper training programs on segregation at the source based on color coding and scientific disposal of BMW must be provided. Such policies must ensure that BMW is safely handled during this infectious pandemic period, as it can pose a serious health threat to healthcare workers, patients, the public, and the environment. To effectively tackle the COVID-19 pandemic, the entire BMW management system must be properly streamlined and disposal methodologies must be optimized sustainably to preserve the health of all humanity while also promoting a clean and green environment.

Nomenclature *SARS-CoV-1*: Severe acute respiratory syndrome coronavirus 1; *SARS-CoV-2*: Severe acute respiratory syndrome coronavirus 2; *COVID-19*: Coronavirus disease 2019; *BMW*: Biomedical Waste; *CPCB*: Central Pollution Control Board; *WHO*: World Health Organization; *BAT*: Best available technology; *MERS*: Middle East Respiratory Syndrome; *PPE*: Personal Protective Equipment; *RDF*: Refuse Derived Fuel; *AIIMS*: All India Institute of Medical Science; *MCF*: Medical care facility; D_n: Daily facemask uses; *P*: Population; *Up*: Urban population (%); F_R: Facemask acceptance rate; F_T: Assumption that each person in the general population uses one facemask daily

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