Biomedical waste generation and management during COVID-19 pandemic in India: challenges and possible management strategies

Ashish Dehal^{1,2} · Atul Narayan Vaidya¹ · Asirvatham Ramesh Kumar^{1,2}

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Abstract

The COVID-19 pandemic has resulted in the massive generation of biomedical waste (BMW) and plastic waste (PW). This sudden spike in BMW and PW has created challenges to the existing waste management infrastructure, especially in developing countries. Safe disposal of PW and BMW is essential; otherwise, this virus will lead to a waste pandemic. This paper reviews the generation of BMW and PW before and during the COVID-19 pandemic, the regulatory framework for BMW management, policy interventions for COVID-19-based BMW (C-BMW), the capacity of BMW treatment and disposal facilities to cope with the challenges, possible management strategies, and perspectives in the Indian context. This study indicated that policy intervention helped minimize the general waste treated as C-BMW, especially during the second pandemic. Inadequacy of common BMW treatment facilities' (CBMWTFs) capacity to cope with the BMW daily generation was observed in some states resulting in compromised treatment conditions. Suggestions for better management of BMW and PW include decontamination of used personal protective equipment (PPEs) and recycling, alternate materials for PPEs, segregation strategies, and use of BMW for co-processing in cement kilns. All upcoming CBMWTFs should be equipped with higher capacity and efficient incinerators for the sound management of BMW. Post-pandemic monitoring of environmental compartments is imperative to assess the possible impacts of pandemic waste.

Keywords Biomedical waste · Common biomedical waste incineration facility · COVID-19 pandemic · Municipal solid waste · Personal protective equipment · Policy intervention · Single-use plastics

Introduction

It is beyond the wildest imagination; the whole world would be afflicted and stranded by a virus of size 50 to 200-nm diameter, the SARS-CoV2 (Ramteke and Sahu 2020). The COVID-19 disease outbreak has generated a worldwide pandemic in economic, social, and environmental repercussions (Ikram et al. 2020; Singh et al. 2020a; Rayani et al. 2021; Yousefi et al. 2021). The virus has led to more than 189 million (M) cases worldwide and 4 M deaths up to 15th

July 2021 (worldometer 2021). India stands at the 2nd position in the total number of COVID patients after the USA. In the present situation, the growth rate of COVID cases in India is the highest among all countries. The total number of confirmed cases in India was more than 31 M, and 0.4 M deaths were reported till 15th July 2021 (worldometer 2021). In this pandemic situation, public health safety has become the priority of all governments.

Several countries have imposed lockdowns and curfews to safeguard the public from this novel virus (Kulkarni and Anantharama 2020; Irfan et al. 2021). The government of India introduced a countrywide lockdown from 25th March 2020 as a critical move to combat the transmission of the COVID-19 virus. The first phase of lockdown lasted for 21 days. The increase in COVID-19 patients in India further led to the 2nd, 3rd, and 4th phases of lockdown, which extended until 30th May 2020 (Gangwar and Ray 2021).

The Government of India (GoI) issued new guidelines in June 2020, which enabled the reopening of commercial establishments, resumption of public transport, and various other

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✉ Asirvatham Ramesh Kumar
ar_kumar@neeri.res.in

¹ Chemical and Hazardous Waste Management Division, CSIR-National Environmental Engineering Research Institute, Nagpur 440020, India

² Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

activities to improve the economy (GoI, <https://www.mha.gov.in/>). The first phase (1st June–30th June) of reopening was termed “Unlock 1.0”. In this phase, earlier lockdown restrictions need to be imposed in containment zones only, while some activities were allowed in other zones in a phased manner. According to these guidelines, large gatherings were prohibited. In all places, night curfews were in effect from 9 p.m. to 5 a.m., and state administrations were given authority to impose appropriate restrictions on all activities.

Similarly, unlock guidelines 2.0, 3.0, 4.0, 5.0, and 6.0 were issued with relaxation to various activities (GoI, <https://www.mha.gov.in/>). The first wave of COVID-19 in India was reported from January 2020 to February 2021. The peak of the first wave was observed in September 2020, with more than 1 M active cases on 18th September 2020. The decline in the number of active cases in India was reported till February 2021. With the surge of the 2nd wave (February 2021 onwards), many states in India re-introduced the lockdowns. The peak of the 2nd wave was observed in May 2021, with more than 3.7 M active cases on 9th May 2021.

Online purchasing of consumer goods has become the preferred shopping mode (Rume and Islam 2020; Tabish et al. 2020; Irfan et al. 2021). The online way has also ensured the survival of services like retailing, catering which experienced significant losses due to lockdown at the pandemic's beginning (Liu et al. 2021). In this situation, plastic packaging has become a necessity for delivering goods. Single-use plastics (SUPs) have been extensively used for packaging due to economic and safety reasons (Liu et al. 2021; Parashar and Hait 2021).

Even before the emergence and dissemination of COVID-19, many developing countries were under stress for managing biomedical waste (BMW) and plastic waste (PW) (Kulkarni and Anantharama 2020; Nzediegwu and Chang 2020). Copious use of medical technologies in hospitals and safety measures to stop the dissemination of the COVID-19 have led to tremendous increase in BMW generation. The sharp increase in personal protective equipment (PPEs), such as aprons, boots, face shields, gloves, goggles, masks, sanitizers, and other medical gears, including bandages, plastic containers, syringes, testing kits, tissues (shown in Figure 1) have drastically altered the BMW composition (Das et al. 2021a, b; Praveena and Aris 2021). Thus, the pandemic generated more pressure on the existing waste management system (Benson et al. 2021; Haque et al. 2021; Parashar and Hait 2021; Roy and Chaube 2021). The PPEs mainly consist of polymers such as low-density polyethylene (LDPE), polypropylene (PP), polyurethane (PU), polyvinyl chloride (PVC), and polycarbonate (PC). In contrast, packaging materials primarily consist of high-density polyethylene (HDPE), LDPE, polystyrene (PS), and polyethylene

terephthalate (PET). Among these, PET and HDPE are widely recyclable polymers, and the rest are difficult to recycle or rarely recycled (Klemeš et al. 2020; Parashar and Hait 2021; Silva et al. 2021). The sharp rise of waste generation has disrupted even the most reputed global waste management facilities (Thind et al. 2021).

Plastics have driven scientific and technical advances in every field due to their flexibility, affordability, and durability. Plastic incorporates superb versatility, strength-to-weight ratio, water resistance, and insulating properties (Chen et al. 2020; Klemeš et al. 2020). Due to these characteristics, plastics are indispensable in the healthcare system, mainly for single-use diagnostic kits and devices. India generates about 9200 t/day of PW, with a total generation of more than 3.3 million t per year (CPCB 2019a). The major PW-generating Indian states are Maharashtra, Tamil Nadu, Gujarat, and West Bengal. To check the growing PW generation, 22 states/union territories (UTs) of India have completely banned, and seven states have partially banned SUP carry bags (CPCB 2019a). But now, the spread of COVID-19 has become an obstacle to implement the ban on SUPs. This is seen as a compromise of the policy during the pandemic as human health is most important than anything else. Contrary to the common belief that plastic is not environment friendly, these SUPs have saved millions from contracting the infection. However, it is pretty common to see the littering of used PPEs due to negligence on the part of individuals that causes harm to the environment and human health (Rowan and Laffey 2021). The surge in the BMW generation during the pandemic is inevitable; however, lessons should be learned to deal with any such outbreak that increases waste in the future. The objectives of this article are to review the regulatory framework, institutional capacity, and the status of BMW management before and during the pandemic in India. Perspectives on the effective management of BMW during any such future events are also discussed. We used BMW data published by the regulatory agency Central Pollution Control Board (CPCB), advisories issued by the Government of India, in addition to keyword searches made in Scopus and Web of Science databases. To the best of our knowledge, this is the first article, which comprehensively reviews the regulatory framework, C-MBW generation vis-à-vis the treatment capacity of various states of India.

Healthcare/hospital waste composition

Health care waste (HCW) includes all the waste generated by medical facilities. It comprises waste produced during testing, treatment, or vaccination of humans or animals. The quantity of general (non-hazardous) waste is 70–80% of total waste generated by health care facilities (HCFs) (WHO 2018; Das

Fig. 1 BMW generation during COVID-19

et al. 2021b). Figure 2 shows the composition of HCW/hospital waste (CPCB 2016a; Das et al. 2021b). BMW comprises the waste generated during the diagnosis and treatment of patients, excluding the general waste. Typical BMW generators are HCFs, blood banks, clinics, hospitals, nursing homes, research institutions, treatment units, etc.

According to a WHO report, HCW in developing countries is often not adequately segregated, thereby making the actual amount of BMW much higher (WHO 2018; Nzediegwu and

Chang 2020). In India, BMW is managed according to BMW Management Rules, 2016 (CPCB 2016a).

BMW generation scenario in India before COVID-19 outbreak

India generates about 619 t/day of BMW. Figures 3 and 4 show the state/UT wise generation of BMW for the year

Fig. 2 Composition of HCF/hospital waste

Fig. 3 BMW generation of different states/UTs in 2019

2019. The top five states that generated 47% of BMW were Karnataka, Maharashtra, Tamil Nadu, Uttar Pradesh, and Kerala. Among all states, Karnataka generated the highest BMW, accounting for 77.5 t/day, and Arunachal Pradesh generated the lowest quantity, 0.4 t/day. Among all UTs, Delhi generated the highest BMW, i.e., 28.8 t/day, and Lakshadweep generated the lowest quantity of BMW, 0.1 t/day (CPCB 2019b).

Regulatory framework of BMW management

The BMW Management Rules, 2016 is the comprehensive regulatory framework followed by India (CPCB 2016a). At HCFs, BMW is segregated into yellow, red, blue, and white categories of waste. The yellow category is also called infectious waste or incinerable waste. Different treatment procedures are adopted for the four categories of wastes. Figure 5

shows the treatment techniques and the disposal methods adopted to the four categories of BMW (CPCB 2016a, b, c).

Incinerators in common BMW treatment facilities

Incineration of medical waste is the most common treatment method adopted in several countries. Available incineration technologies include pyrolytic chamber/modular, rotary kiln, and fluidized bed incinerators. The selection of an appropriate incineration technology depends on factors such as calorific value of waste, moisture content, volume, composition, and cost factor. For more details, the reader may refer relevant literature (UNEP 2012). In India, dual chamber modular incinerators, which operate under the “controlled air” principle, are installed in all common BMW treatment facilities (CBMWTFs). It is economical compared to other types; however, it has the limitation of incineration capacity. All incineration technologies

Fig. 4 BMW generation of different states/UTs in 2019

Fig. 5 Regulatory framework for BMW

have certain limitations. In recent years, non-incineration technologies such as high-temperature steam and microwave-based technologies are becoming popular in some countries (Chen et al. 2013a; Khoo et al. 2021). More details could be found elsewhere (Zimmermann 2017).

The yellow category (Y-BMW) is collected in non-chlorinated bags and is incinerated in CBMWTFs. All the CBMWTFs have double chamber modular incineration system, with incineration capacity ranging from 50 to 200 kg/h. The incinerators are designed for the combustion efficiency of >99%. Wastes are fed into the primary chamber in batches of about one-fifth the capacity of the chamber. The primary and secondary chamber temperatures are maintained at a minimum of 800 °C and 1050 ± 50 °C, respectively. The air supply is regulated between 30 and 80% and 120 and 170% of the stoichiometric volume in the primary and secondary chambers, respectively (CPCB 2016b, c). This controlled air supply in the primary chamber and excess air in the secondary chamber minimize particulate matter generation and efficient destruction of organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans. According to BMW regulations, flue gases' residence time (RT) in the secondary chamber should be at least 2 s. However, most of the CBMWTFs constructed before 2016 have been designed for 1-s RT. All incinerators are equipped with wet/packed bed scrubbers to remove particulate matter and acidic vapors. Few incinerators that came up after 2016 are equipped with activated carbon filters to remove dioxins and furans. The flue gases are let out via a stack of 30 m in height. Ash generated in incinerators is disposed of in hazardous waste landfills (CPCB 2016a, b, c).

Status of BMW treatment and disposal facilities in India

There are 322,425 HCFs in India, out of which 153,885 are granted authorization under the BMW rules 2016, and more than 29,000 HCFs violated the BMW rules in 2019 (CPCB 2019b). BMW generated in India is managed by CBMWTFs and captive BMW treatment systems (C-BMWTS). CBMWTFs are common infrastructural facilities where BMW from multiple HCFs is treated and disposed of in economical and viable ways. There are 202 CBMWTFs in India, and another 35 are under construction stage. C-BMWTS treat and dispose of the BMW generated from individual HCF. The BMW Management Rules 2016 restrict the installation of C-BMWTS if CBMWTF is available within 75 km of distance. CBMWTFs avoid the scattering of treatment systems in the area/city. In addition, these facilities are much easier and economical to operate and monitor compared to scattered C-BMWTS. Still, more than 18,000 HCFs in India have C-BMWTS. Only 136 HCFs have captive incinerators, which means the rest of HCFs only use deep burial methods. India generates 619 t/day of BMW, out of which CBMWTFs treat about 489 t/day, 55 t/day by C-BMWTS, and the remaining 74 t/day is disposed of in remote areas by deep burial method (CPCB 2016a, 2019b). Deep burial of waste in remote areas is adopted due to distance constraints between the HCFs and CBMWTFs.

The total capacity of all the CBMWTFs is about 840 t/day (Shammi et al. 2021). The incinerators are very difficult to operate if they are fed with more than 70% of their capacity. India generates 619 t/day of BMW, which is less than 840

t/day, still many states have exceeded their utilization capacity. In states, namely Assam, Kerala, Tamil Nadu, Jammu Kashmir, Meghalaya, Odisha, and Tripura, the capacity utilization of existing facilities has already exceeded 70%. Therefore, these states should conduct gap analyses in each coverage area to determine the need for additional facilities. Some states/UTs, viz. Sikkim, Nagaland, Mizoram, Goa, Arunachal Pradesh, Andaman Nicobar, and Dadar Nagar Haveli, do not have any CBMWTFs; hence, these states/UTs should set up new facilities of suitable capacities (CPCB 2019b).

Increase in BMW during the COVID-19 pandemic

In India, the composition and distribution of BMW are highly variable which depends on various factors. These include the efficiency of segregation at source, knowledge of healthcare workers, accessibility, and availability of CBMWTFs. Studies also indicate that the generation and type of BMW also depend on HCFs, recyclable and reusable items, the number of patients handled daily, etc. (Devi et al. 2019; Thind et al. 2021). Due to the COVID-19 outbreak, the sharp increase of PPEs, other medical gears, etc., have drastically affected the waste management system. More than 340 M passengers were handled by airports in India during 2020, which includes 274 M domestic and 66 M international passengers. Due to COVID-19, all the airlines started providing PPE kits to the passengers. It means, approximately 340 M aprons, face masks, face shields, gloves, sanitizer sachets were used by air travellers in India (<https://www.statista.com/statistics/588028/passengers-boarded-by-type-by-indian-air-carriers/>). India requires about 2.5 M of PPE kits every day to combat the spread of COVID-19 virus (Parashar and Hait 2021). The material composition of PPEs include about 20–25% by weight of plastic, especially PP (Singh et al. 2020a). This vast quantity of plastic is destined for landfilling or incineration, thus causes environmental pollution.

Figures 6, 7, and 8 show the COVID-19-based BMW (C-BMW) generation in Indian states/UTs during September 2020 and May 2021. The major contributing states/UTs to C-BMW during the 1st wave (September 2020) were Gujrat, Tamil Nadu, Maharashtra, Uttar Pradesh, Kerala, West Bengal, Delhi, Madhya Pradesh, Haryana, and Punjab, which contributed about 80% of the total C-BMW. The average C-BMW generation was 183 t/day during September 2020. During the 2nd wave (May 2021), the average C-BMW generation was 203 t/day. The top contributing states/UTs were Kerala, Gujrat, Maharashtra, Delhi, Karnataka, Uttar Pradesh, Tamil Nadu, Haryana, Andhra Pradesh, and Madhya Pradesh. Lakshadweep generated the lowest quantity of C-BMW during both waves, 10 kg/day (CPCB 2020a).

Number of active cases and C-BMW generation

Figure 9 shows the positive correlation between the number of COVID-19 active cases and the average C-BMW generation. Also, it is observed that as the number of COVID-19 active cases increases, the C-BMW also increases and vice versa. During the peak of the 1st wave, the C-BMW generation was 183 t/day, and during the peak of the 2nd wave, the C-BMW generation was around 203 t/day. The number of active cases during the peak of the 2nd wave was 3.7 times that of the 1st wave. Still, the C-BMW generation rate differed only by about 20 t/day. The knowledge about the COVID-19 virus and its dissemination, the decrease in the fear, and timely policy intervention by CPCB on segregation and management helped reduce waste generated during the second wave. It is to be noted that during the 2nd wave, only patients with severe symptoms with other comorbidities were advised for hospitalization, and the rest were advised to remain in home isolation/quarantine. C-BMW generated at home do not have access to CBMWTFs; hence, they were generally disposed of with municipal solid waste (MSW). This practice has increased the MSW generation drastically in India and in other developing countries as well (Kulkarni and Anantharama 2020; Vanapalli et al. 2021; Das et al. 2021a). Even developed countries with a well-established MSW management system reported a surge in MSW generation due to the disposal of PPEs in MSW (Das et al. 2021b).

BMW and PW generation from vaccination centers

COVID-19 pandemic has already added a massive amount of PW and BMW and will continue to generate PW and BMW until it ceases. Many organizations are working on medicines and vaccines for the novel virus to stop this pandemic. Several pharmaceutical companies have successfully launched their vaccines in the market. Bharat Biotech developed India's first indigenous vaccine, the Covaxin. The Serum Institute of India (SII) introduced the Covishield vaccine in collaboration with Oxford-Astra Zeneca. The vaccination program in India was launched on 16th January 2021. Although vaccination drive is necessary for the current situation, it also adds a vast amount of BMW and PW such as syringes, gloves, and vaccine containers. India has become the world's fastest country to administer 140 M vaccine doses in just 100 days (<https://www.covid19india.org/>). The current population of India is more than 1.39 billion (worldometer 2021). It is estimated that the vaccination of the entire country will generate about 2.78 billion syringes, gloves, and vaccine containers. Therefore, it is very essential to properly collect, segregate, and dispose of all the waste generated during vaccination.

Fig. 6 The average C-BMW generation by different states/UTs in India (kg/day)

Waste management facilities commonly cater to steady-state flow of waste with moderate fluctuations in the composition and quantity (Parashar and Hait 2021). The sudden change in waste quantity and composition caused by the pandemic affected the regular operations of present treatment facilities. Due to the widespread use of PPEs, medical gears, and SUPs, the world is on the verge of devising a worldwide waste pandemic unless it is successfully monitored and addressed. Inadequate PW management, littering poses the threat of viral spread and pollutes the terrestrial and aquatic environments (Sarkodie and Owusu 2020). Improper handling of wastes that contaminate the environment could also be caused by the dearth and discrepancies in current waste management processes, such as limited personnel and capacity constraints.

Inadequate infrastructure facilities for BMW treatment

In the present scenario, onsite waste segregation is minimal due to the sudden rise in BMW generation, fewer employees available, and the fear of infection in HCFs. This poses a high probability of infection risk to waste management agencies responsible for the collection, segregation, treatment, and disposal. India's current BMW generation has reached more than 800 t/day (Chand et al. 2021). Most of the CBMWTFs have small incinerators, i.e., 50–200 kg/h, and some states are not in a position to handle BMW even before the pandemic. Inequalities in the geographical distribution of CBMWTFs and the higher number of COVID-19 cases reported in some

Fig. 7 The average C-BMW generation by different states/UTs in India (kg/day)

Fig. 8 Top ten states/UTs generating C-BMW during May 2021

states further aggravated the situation. Considering the logistics and employees involved in the BMW management, it is observed that incinerators working >70% of their capacity are likely to face difficulties in the operation (CPCB 2020a, b). The states such as Andhra Pradesh, Chhattisgarh, Haryana, Madhya Pradesh, Maharashtra, and Telangana have the adequate capacity of CBMWTFs. The incinerators in states viz. Bihar, Jammu Kashmir, Karnataka, Kerala, Odisha, Rajasthan, Tamil Nadu, Uttar Pradesh have exceeded the 70% utilization capacity, thus need to identify alternate incinerators/disposal options (Table 1). These circumstances

would certainly lead to compromised or inefficient treatment conditions. (CPCB 2019b).

Policy intervention for C-BMW management

The COVID-19 disease outbreak has led to an exceptionally high volume of BMW due to PPEs and other dedicated patient care items used by health care professionals and patients. In addition, the use of face masks, hand sanitizers, and surface disinfectants has become mandatory for the general public to

Fig. 9 The relationship between the number of active cases in India in the mid of the month and C-BMW generation

Table 1 Inequalities in the geographical distribution and capacity utilization of CBMWTFs in some states of India

Name of state	Number of CBMWTF engaged	Authorized capacity (t/day)	BMW (t/day)*	C-BMW (t/day)**	Total (BMW + C-BMW), t/day	Capacity utilization (%)
Andhra Pradesh	12	44.4	15.1	9.99	25.09	56.5
Assam	1	7.2	8.8	0.52	9.32	129.4
Bihar	4	45.3	34.8	1.06	35.86	79.2
Chandigarh	1	6.5	3.9	1.91	5.81	89.4
Chhattisgarh	4	22.8	7.07	2.76	9.83	43.1
Delhi	2	62.8	28.8	18.79	47.59	75.8
Gujarat	20	103.9	36.4	21.98	58.38	56.2
Haryana	11	83.4	14.8	13.11	27.91	33.5
Himachal Pradesh	2	9.2	3.4	2.27	5.67	61.6
Jammu and Kashmir	3	9.8	5.9	2.49	8.39	85.6
Jharkhand	4	13.1	7.6	0.56	8.16	62.3
Karnataka	27	108.4	77.5	16.91	94.41	87.1
Kerala	1	48	42.9	23.71	66.61	138.8
Madhya Pradesh	12	46.5	17.8	7.32	25.12	54.0
Maharashtra	31	130.9	62.3	19.02	81.32	62.1
Manipur	1	2.6	1	0.13	1.13	43.5
Odisha	5	14.9	18	6.65	24.65	165.4
Punjab	5	29.1	16.05	4	20.05	68.9
Rajasthan	8	35.3	20.7	4.98	25.68	72.7
Tamil Nadu	8	72.9	58.3	13.57	71.87	98.6
Telangana	11	118.7	20.5	4.96	25.46	21.4
Uttarakhand	2	7.5	3.8	1.98	5.78	77.1
Uttar Pradesh	18	91.3	52.5	15.91	68.41	74.9
West Bengal	6	79.9	41.6	5.72	47.32	59.2

* Denotes the BMW generation of 2019 and ** denotes the C-BMW generation for May 2021

prevent the highly contagious virus. Furthermore, numerous latest materials launched in the market for detection, testing, diagnostic, and treatment of patients also contributed towards BMW. Advisories issued by the World Health Organization (WHO 2020) helped countries to make appropriate policy decisions regarding the safe disposal of HCW. The Basel Convention on the transboundary movement of hazardous wastes and their disposal has issued guidelines immediately after the onset of the pandemic, i.e., 20th March 2020. The Basel Convention urged all countries to recognize BMW management as an essential public health service to minimize possible secondary impacts upon health and the environment. In India, the CPCB is responsible for the implementation of BMW (2016) rules. CPCB issued guidelines to treat BMW management as “essential services” and ensured the uninterrupted movement of vehicles and people involved in BMW management. Further policy interventions include an adequate supply of yellow, red, white, and blue bags/containers to all the hospitals and quarantine facilities for onsite segregation

and collection of waste. For final disposal, BMW should be transferred to CBMWTFs. If CBMWTFs are not available, the waste produced can also be taken to the nearest authorized hospital for incineration at C-BMWTS. The guidelines mandated the use of PPEs by all the people dealing with BMW in isolation wards. Figure 10 depicts the BMW category, waste types, bags/containers used for storage, treatment, and disposal (CPCB 2016a, b, c).

CPCB issued the first policy intervention on 18th March 2020 for the safe handling and disposal of C-BMW (CPCB 2020c). These were in addition to the existing BMW and Solid Waste Management (SWM) Rules, 2016 (CPCB 2016c, d). These guidelines suggest using double-layered bags for collecting waste from quarantine/isolation centers to assure sufficient strength and safeguard from any leakages. Usage of dedicated bins labeled as “COVID-19 waste” is suggested. The collected waste should be transferred to CBMWTFs or C-BMWTS for safe disposal. All the personnel handling C-BMW should be provided with PPE kits. The

Fig. 10 BMW categories, type of bags or containers used, and their disposal

bins, containers, and trolleys used for C-BMW transportation or storage should be thoroughly disinfected with 1% NaOCl solution (CPCB 2020c). During the implementation of the first guidelines, the reported number of cases was about 200 in India (worldometer 2021), and C-BMW's generation was far less compared to the current scenario. Thus, it was comparatively easy to dispose of the total generated C-BMW in CBMWTFs. The increase in knowledge about the health and environmental impacts, the severity of the virus, and an increase in COVID-19 cases in India, vis-à-vis the global best practices, led to CPCB issue 2nd, 3rd, and 4th amendments in just 5–6 months (Kulkarni and Anantharama 2020; Sangkham 2020).

The second revision of guidelines was issued on 19th April 2020. The reported COVID-19 cases were more than 16,000 on 18th April 2020 (worldometer 2021). Diapers used by

COVID-19 patients who cannot use toilets are to be treated as Y-BMW or incinerable waste. Used masks, caps, head covers, plastic/semi-plastic coverall, shoe cover, disposable linen gowns, etc., are to be stored in yellow containers. PPEs involving face shield, splash-proof aprons, goggles, hazmat suit, pre-treated viral transport media, vacutainers, plastic vials, cryovials, pipette tips, etc., should be stored in red bags. Gloves and masks generated from households are to be wrapped in paper bags and stored for at least 72 h before disposal. This storage period is aimed to deactivate the virus residing on certain surfaces (Kampf et al. 2020). It is also suggested to cut the masks, gloves before disposal to avoid reuse. These guidelines also permit the disposal of Y-BMW in remote areas by deep burials in the absence of CBMWTFs or C-BMWTS (CPCB 2020d).

The 3rd revised guidelines were issued on 10th June 2020 by CPCB. The total number of COVID-19 cases increased to 0.25 M in India on 9th June 2020 (worldometer 2021). In this amendment, the guidelines on the segregation of BMW and general solid waste (GSW) were given importance due to the surge in GSW generation. In addition, this amendment also addresses the safety of workers associated with CBMWTFs in handling BMW and other wastes generated from HCFs treating COVID-19 patients, homecare, and quarantine centers. This amendment suggested the use of color-coded containers with foot-driven lids. GSW such as wrappers of syringes, medicines, empty juice or water bottles, discarded papers or carton boxes, and fruit peel-offs, which were not contaminated by COVID-19 patient's body fluids/blood, should be collected and disposed of as per SWM rules 2016 (CPCB 2016d). Non-disposable products, which could be cleaned, handled, and disinfected, must be reused to decrease waste generation. Items such as disposable plates, glass, food leftover, used tissues, toiletries, and masks, used by COVID-19 patients, shall be treated as Y-BMW. Due to the large quantity of Y-BMW generation beyond the capacities of CBMWTFs and C-BMWTS, these guidelines permit BMW disposal by hazardous waste (HW) incinerators. In such scenario, arrangements for separate handling and feeding should be ensured. Waste handlers should be aware of basic knowledge on hand hygiene, social distancing, PPEs, waste segregation, and disposal (CPCB 2020e; WHO 2020).

The 4th revision of guidelines was issued on 17th July 2020 by CPCB. The total number of COVID-19 cases reached more than 1 M in India on 16th July 2020 (Worldometer 2021). This amendment issued revised guidelines for segregation of GSW and BMW from isolation, quarantine centers, homecare, and HCFs. Yellow-colored bins should not be used for the collection of GSW. Segregation of BMW and GSW should be done at the waste generation site itself. The discarded PPE used by the general public should be stored in separate containers for at least 72 h; after that, it can be shredded and disposed of as dry GSW. PPEs doffed by health personnel accompanying the dead body of COVID-19 patients to graveyard/crematories should be treated as BMW. Used gloves and masks from graveyards/crematorium visitors should be collected in separate containers/bins and stored at least 72 h before disposal as GSW (CPCB 2020f).

Another remarkable policy intervention to track the C-BMW management has been the launch of the software application, "COVID19BMW," for monitoring the generation, collection, and disposal of C-BMW from various HCFs, homecare centers, isolation/quarantine areas, sample collection centers, testing areas, etc. HCFs and CBMWTF operators are mandated to use this App to report the quantity of waste generated and treated. This App enables knowledge sharing among different stakeholders involved.

Although CPCB issued policy guidelines based on the experience and global best practices, BMW management during the COVID-19 pandemic appears inadequate due to the weak infrastructural and regulatory issues. This is manifested by the National Green Tribunal's (NGT) intervention. This judicial body deals with environmental problems in India on the matter related to the disposal of C-BMW (CPCB 2020b). The NGT, in its order, pointed out regulatory and implementation gaps exist in the (a) deep burial methods, (b) absence of BMW collection, storage, and disposal mechanism in villages and rural areas, (c) disposal with general waste, and (d) lack of awareness among stakeholders. India's rural population is about 65%; hence, the impact of improper methods of BMW disposal may have severe environmental and public health consequences. This is mainly due to the absence of adequate infrastructural requirements for the sound management of BMW and general waste in India and most other developing countries (Nzediegwu and Chang 2020). Poor MSW management and improper disposal of used PPEs may result in the spread of the COVID-19 virus, given its persistence up to 9 days (Kampf et al. 2020).

Environmental and health consequences of inefficient incineration of BMW

Incineration is the principal mode of disposal of C-BMW at CBMWTFs or C-BMWTS. The quantity of Y-BMW ranges from 34 to 70% of the total BMW, with an average of 50.4% (Thind et al. 2021). Incineration involves a remarkable reduction in waste volume and weight. This process is adopted for waste that is neither reusable nor recyclable due to its highly infectious nature. Used PPEs and SUP products in C-BMW are likely to generate more toxic organic compounds such as dioxins, furans, PAHs, and polychlorinated biphenyls (PCBs), during incineration. PPEs generally contain 25% of polymers such as PP and PE, and studies have shown that incineration of plastics produces more unintentional persistent organic pollutants such as PCBs, PAHs, dioxins, and furans (Shibamoto et al. 2007; Chen et al. 2013b; Singh et al. 2020a, b). In addition, microplastics, one of the emerging environmental pollutants, are detected in incineration ashes during recent times (Shen et al. 2021).

During the first and second wave of COVID, the surge in the generation of BMW has been experienced by various CBMWTFs. Even before the onset of COVID-19, some states have already exceeded the 70% utilization of the authorized capacity (CPCB 2019b). Table 1 indicates the exceedance of treatment capacity of several states, but still, these states are compelled to treat the BMW in CBMWTFs available within the states. Feeding more waste, i.e., above one-fifth of the chamber capacity into the primary chamber, may not result in the recommended combustion efficiency of 99%, leading to

incomplete combustion. To combat this, CPCB granted authorization to use hazardous waste incinerators (HWI) for BMW incineration. However, HWI are very few in India (only 12); most are located in industrialized states such as Gujarat, Maharashtra, Ghaziabad (Delhi), and Tamil Nadu, and may not be much helpful in reducing the burden on the CBMWTFs. Details of BMW incinerated in HWI are not available.

Due to the lack of engineered landfills in India, the PPEs disposed of with MSW are predominantly destined to informal dumping sites. PPEs are mainly made of non-woven spunbond meltbond spunbond (SMS) fabric, which can degrade into microplastics. Similarly, SUPs are lightweight, easily carried away by wind and scattered over land and water bodies, and may pose hazards to terrestrial and aquatic organisms. SUPs may further increase the visual plastic pollution as well as microplastic levels in land and water resources in the near future. The deep burial method adopted by HCFs having captive treatment facilities may also likely to increase soil microplastic contamination. However, it remains to be seen, as data on the disposal of BMW by deep burial methods are currently not available.

Possible management strategies and solutions

Inadequate infrastructure for waste treatment and disposal is one of the major issues in developing countries, including India. During pandemic times, it is always human health and safety which get priority over other issues. However, if adequate attention is not paid, the pandemic waste would pose severe environmental health consequences in the future. Though India has responded well with various policy interventions based on experience gained and quick in adopting the policy guidelines of WHO, it should improve the infrastructure for the management of MSW, BMW, and PW for the successful implementation of these interventions. It might take some time to see how accurately the added waste will impact the environment. Moreover, the BMW and plastic produced during the pandemic could be used as a benchmark for emergency and protracted waste management practices, enabling us to create a safer and healthier tomorrow. Robust, viable approaches and strategies are needed to deal with waste generated during the global pandemic. Amelioration in technology along with sustainability is required to deal with the pandemic. Some plans or initiatives could need immediate attention and action, whereas others may require considerable attention in the long run (Vanapalli et al. 2021). The emergency preparedness and safety systems are obligatory for all countries to tackle the enormous rise of BMW and SUPs during the pandemic.

- The SUPs and BMW should be disposed of safely to barricade virus spread and curtail the adverse effects on the environment. Color-coded bins should be used to ensure effective collection and disposal (Datta et al. 2018; Das et al. 2021b). The BMW management guidelines (CPCB 2016a, 2020f) should be referred to and adopted to segregate, collect, store, transport, and dispose of the waste generated. Instead of any interim actions and transitional policies, a universal strategic plan has to be drawn up. Local authorities may provide specific color-coded bags to the households (home quarantine centers) to discard the PPEs. This will improve onsite segregation of BMW. Furthermore, specific color-coded bins may be placed in community centers/public places.
- Investment in health infrastructure and hiring of skilled health professionals are required to improve the treatment capacity (Shammi et al. 2020; Deepak et al. 2021). The successive usage of mobile equipment and expanding everyday treatment capabilities of stationary stations are appropriate responses to tackle the COVID-19 pandemic. Several mobile incinerators of > 50 t/day capacity were installed in Wuhan city to tackle the C-BMW. The mobile facilities are helpful in pandemic situations but its sustainability is to be ensured (Shammi et al. 2021). This is true for countries such as India, as the generation of C-BMW is highly variable. For instance, during May 2021, the number of active cases in northern states of India was comparatively less than that in southern states and so the C-BMW generation. One possible solution is shifting mobile incinerators to other states in such situations.
- There is an urgency to increase the treatment capacity of incinerators in CBMWTFs and C-BMWTS. Currently, most of the incinerators in India are of the modular type, with capacity ranging from 50 to 200 kg/h. Due to the massive C-BMW generation, there is a need to switch to higher capacity modular, rotary, and fluidized bed incinerators. But at the same time, one should look at the scenario and use of these higher capacity incinerators after the COVID-19 pandemic. Thus, at the designing stage, focus should be on designing appropriate capacity incinerators depending on the population and number of HCFs. The current limit of 75-km radius for BMW collection could be increased for large capacity incinerators. All incinerators should be equipped with suitable air-pollution control and monitoring devices. Activated carbon filters can be utilized to remove dioxins, furans, and other unintentional POPs.
- Given the current compromised SUP and PPEs disposal method, it is necessary to increase monitoring (aquatic, terrestrial, and aerial surveys) of PW under the post-COVID-19 situation. Studies should address the environmental fate, behavior, degradability, and effects of used PPEs, plastic additives, the potential for pathogens

transfer, and sorption/desorption capacities of POPs like pollutants.

- Considering the public health and safety during the pandemic, there is a need to develop more advanced and automated systems (based on the Internet of Things) for BMW management with the minimum number of workers involved (Das et al. 2021b). Incorporating artificial intelligence in existing and emerging facilities for segregation, processing, etc., will decrease the burden on manual facilities and help waste management systems operate more efficiently.
- HCFs must consider various decontamination approaches for recycling and reuse of PPEs. Different disinfection approaches such as hydrogen peroxide vapors, washing, UV germicidal lamps, moist heat, gamma irradiation, 75% alcohol solution, ethylene oxide, etc., are used in other countries (Ilyas et al. 2020; Kampf et al. 2020; Rowan and Laffey 2020; Khoo et al. 2021; Liu et al. 2021; Mohanan et al. 2021). Decontamination techniques would limit the plastic supply and minimize PW generation while facilitating sustainability practices. Reusable and recyclable products are to be encouraged (Singh et al. 2020b). Instead of plastic-based, widely available masks, the use of fabric masks should be encouraged (Silva et al. 2020). If people start wearing reusable masks rather than single-use masks, it can diminish the waste generation and risk of contamination due to disposal. Reusable masks will also help in securing the supply of single-use masks for health workers.
- The emphasis should be on developing innovative and sustainable ways for recycling mixed and other complex plastic products. High recyclability rates and high-quality goods could be achieved by incorporating artificial intelligence into the segregating and processing stages. It is essential to recognize and reward well-operating recycling plants and highlight them in the media to encourage others. Complex and economically unrecyclable materials, such as multi-layer packaging, should be restricted. Policies to reduce multi-layer plastics and promote homogeneous plastic packaging should be formulated as a long-term plan to enhance PW recycling efficiency.
- Modern methods such as hydrothermal carbonization, based on high temperature, and autoclaving pressure techniques can be used for BMW carbonization (Shen et al. 2017; Sharma et al. 2020).
- Co-processing of BMW mainly in cement kilns is an excellent solution to save our planet from the waste pandemic. In this process, the wastes get destroyed at around 1450°C temperature, longer residence time, and leave no residue. Apart from utilizing the energy content of waste, its inorganic portion gets fixed with the clinker and becomes part of cement. Furthermore, the alkaline environment within the kiln helps in neutralizing the acidic gases generated during the co-processing. This method also decreases the demand for non-renewable energy resources such as limestone and coal (CPCB 2017a, b).
- The development of eco-friendly PPE kits should be promoted. The production industry must concentrate on using compostable or biodegradable plastics such as bio-plastics manufactured by biomass usage. Appropriate facilities must be established for managing such bio-plastics. To protect ourselves from the plastic pandemic, we should also opt for refillable soap dispensers and hand sanitizers. The production of such greener goods should be incentivized and rewarded.
- Companies and industries should be encouraged to finance the startups working in PW and BMW management. The resources and funds issued by the industries should be considered as a portion of extended producer responsibility.
- Currently, only construction and demolition wastes (generated mainly during the disasters like earthquakes, hurricanes, and tsunamis) are included in disaster waste. C-BMW and other wastes generated in the future pandemics can also be included in disaster waste; separate rules and regulations should be formed to deal with such waste in the near future.
- Waste management ought to be included in the disaster management plan. Additional directives and response measures should be formulated to respond and manage the waste produced during future pandemics. It is necessary to ensure that the people engaged are well aware of handling BMW, which could be accomplished by establishing a common knowledge-sharing forum.
- Awareness programs, media campaigns must be launched to make the public more aware of the environmental effects of haphazard dumping and poor governance of PW and BMW. The public should also take responsibility for the adequate disposal of PW. Furthermore, to raise awareness among future generations, the environmental impacts of BMW and PW should be introduced in the school curriculum. Efforts to address fear-driven perceptions about the hygiene of recycled and reused materials should also be taken into consideration.

Limitations of the study

The primary objective of this study is to review the regulatory framework and the institutional capacity to manage the unpredictable volume of BMW generation during the COVID-19 pandemic. Data on BMW generation was obtained from published reports of regulatory agencies. Monthly data on BMW generation is available only statewide; hence, it may not be possible to identify “critical areas” where BMW management

requires improvement. Sub-categories of BMW generated and disposed, i.e., yellow, red, blue, and white, are also not available. Considerable quantity of PPE is disposed of with MSW, especially by non-infected people. Also, underreporting of data is an issue in areas where the regulatory mechanism is weak. Despite these limitations, the conclusions and perspectives of this study represent the regional levels and must be helpful to researchers and policymakers.

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Data availability All the data referred in this paper are available in the public domain.

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