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Review

Overcoming challenges due to enhanced biomedical waste generation during COVID-19 pandemic

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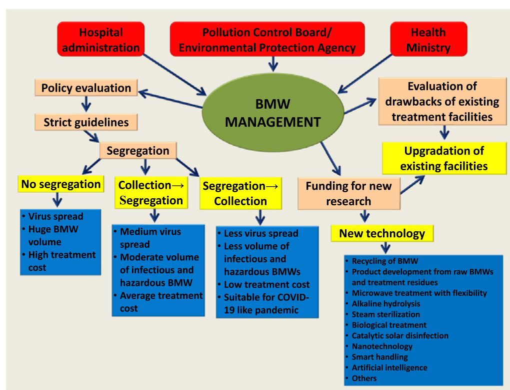
HIGHLIGHTS

- Reasons for enhanced biomedical waste generation during COVID-19 pandemic are explained.
- Drawbacks of different conventional treatment techniques are summarized.
- Scopes of recycling of treatment residues are described.
- Recent advancement in research related to biomedical waste treatment and segregation policies are demonstrated.

GRAPHICAL ABSTRACT



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ABSTRACT

Biomedical wastes (BMWs) are potentially infectious to the environment and health. They are co-dependent and accumulative during the ongoing coronavirus disease-2019(COVID-19) pandemic. In India the standard treatment processes of BMWs are incineration, autoclaving, shredding, and deep burial; however, incineration and autoclaving are the leading techniques applied by many treatment providers. These conventional treatment methods have several drawbacks in terms of energy, cost, and emission. But the actual problem for the treatment providers is the huge and non-uniform flow of the BMWs during the pandemic. The existing treatment methods are lacking flexibility for the non-uniform flow. The Government of India has provisionally approved some new techniques like plasma pyrolysis, sharp/needle blaster, and PIWS-3000 technologies on a trial basis. But they are all found to be inadequate in the pandemic. Therefore, there is an absolute requirement to micromanage the BMWs based on certain parameters for the possible COVID-19 like pandemic in the future. Segregation is a major step of the BMW management. Its guideline may be shuffled as segregation at the entry points followed by collection instead of the existing system of the collection followed by segregation. Other steps like transportation, location of treatment facilities, upgradation of the existing treatment facilities, and new technologies can solve the challenges up to a certain extent. Technologies like microwave treatment, alkaline hydrolysis, steam sterilization, biological treatment, catalytic solar disinfection, and nanotechnology have a lot of scopes for the treatment of BMWs. Hi-tech approaches in handling and transportation are found to be fruitful in the initial steps of BMW management. End products of the treated BMWs can be potentially fabricated for the application in the built environment. Some policies need to be re-evaluated by the health care facilities or government administrations for efficient BMW management.

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Contents

1. Introduction

Civilization, technological advances, and resources consumption are necessary for the development of a country, but they have entitled an unintended negative impact on the urban environment. Presently India is grappling with different issues of the higher volume of diverse wastes. The waste disposal technologies and their methodology have impacted different local and global environmental establishments. During the ongoing novel COVID-19 pandemic, the generation of BMWs at different COVID-19 treatment facilities is increased by many folds due to the new guidelines for their handling, treatment, and disposal implemented by the Central Pollution Control Board(CPCB), Government of India, New Delhi (CPCB, 2020). As per the guidelines, leftover food of patients and disposables like surgical masks, gloves, bib, roll, sheets, wrappers of medicine/syringes, used water bottles, food plates, and semisolid gels are coming under the umbrella of BMW (Hasija et al., 2022; Sarkodie and Owusu, 2021). These additional inclusions result in the generation of huge BMW during the pandemic (Chowdhury et al., 2022). Their daily generation rate has increased from 500 to 750 g per bed before the pandemic to 2500–4000 g per bed during the pandemic. The rate of BMW generated per day is 609tons, and further addition of 164tons per day of COVID-19 related BMWs, including the waste generated from different quarantine homes (Sharma et al., 2020). In India, the amount of BMW was 56898tons from June 2020 to June 2021. Further, the non-uniform flow of the COVID-19 related wastes has confused the BMW quantity evaluation and their management (Richter et al., 2021). The BMWs have assumed an increasing significance in its management and handling procedure due to the statutory demand of different medical administrations of the Government of India. Lacking proper BMW management creates health risks in public, patients, healthcare personnel, and the environment (Nema et al., 2011). The management procedure includes quantity assessment, types, preliminary handling, transportation, treatment, and final disposal of the BMWs (Sharma et al., 2020). So far, the proper management of the categorical wastes has imposed more responsibilities on the medical administrators (Shammi et al., 2022). However, the BMWs can be managed with the application of proper technology to reduce the headache of the medical establishments (Saxena and Srivastava, 2011). For example, about 50% rise in the BMWs has attributed to the food wastes from different COVID-19 hospitals and isolation centers which are non-hazardous and effectively segregated at the source. Therefore, the segregation of BMWs at the entry points is one of the major steps for their management (Dehal et al., 2021). Similarly, upgradation of the current treatment and disposal techniques and development of the new technologies combined with the implementation of some new rules and policies give the ray of light for overcoming the challenges due to the huge BMW generated during the pandemic (Agrawal et al., 2021; Ara et al., 2022; Kumar et al., 2021; Mohan et al., 2022). The present review article summarizes the pros and cons of different existing BMW treatment techniques and future perspectives for the overall BMW management.

2. BMW generation in India during pandemic

According to the CPCB reports from the year 2007 to 2019, there was a steady increase in the amount of BMW generation per day, as shown in Fig. 1 (CPCB, 2020). In 2008, the BMW generation rate was only 410tons per day. In the next ten years, the value increased up to 619tons per day. India has set up different BMW treatment facilities in its states and union territories with a treatment capacity of 800tons per day (Dehal et al., 2021). Fig. 1 shows that the daily generation of BMWs was much less than the treatment capacity; however, 100% treatment was unable to achieve. This may be due to inadequacy in implementing the BMW management policies or incompetent treatment facilities. Fig. 2 shows the percentage of BMWs treated during the above period. The percentage of treatment increased from 2007 to 2011 and remained stationary up to 2016. After 2016 it again decreased steadily up to 2019. This decrease in the treatment percentage needs an urgent evaluation based on the policy-making and environmental impact assessment. During the pandemic, the daily BMW generation rate has suddenly increased up to 850tons per day (Chand et al., 2021). This increased BMW generation rate is the consequence of the sudden increase of the COVID-19 patients and the additional guidelines set up by the CPCB. The COVID-19 related BMWs generation rate is given in Fig. 3, which mimics the pattern of COVID-19 positive

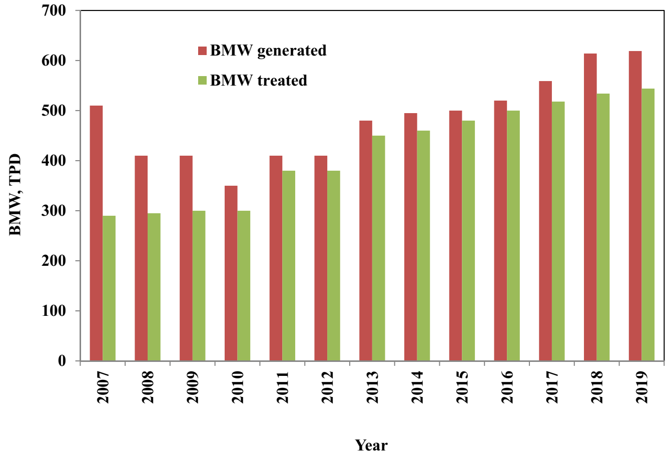

Fig. 1. BMW generated and treated in India from the year 2007 to 2019 in terms of tons per day(TPD). *Data is collected from CPCB website, 2022.

cases in India. The sudden increase in the amount of BMWs during the pandemic has turned out to be extremely harsh for the treatment providers and medical administrators. Therefore, there is an absolute requirement to micromanage the BMWs based on certain parameters for the possible COVID-19 like pandemic in the future (Goswami et al., 2021; Punčochář et al., 2012).

3. Types of BMW

The BMWs are generally different from the normal wastes. They may be either in the form of liquid or solid. Some of them are noninfectious but hazardous and upon disposal without treatment cause environmental pollution. According to the environmental impact, they are of two types i.e. hazardous and non-hazardous (Dehal et al., 2021).

3.1. Hazardous BMW

The hazardous BMWs are generally accounted for 10–25%. There is a certain fraction of the BMWs containing infected human tissues, blood, excreta, etc. They are the carriers of the pathogens like bacteria, viruses, fungi, and parasites. Generally, pathological or surgical wastes like human anatomical tissues, fetuses, organs, and body fluids are carriers of the pathogens. The biochemical laboratory generates bacterial and viral cultures, stock and used media, quality control reagents, serological enzymes, and disposable single-use apparatus. They are potentially being contaminated by different pathogens as well as contain toxic or radioactive

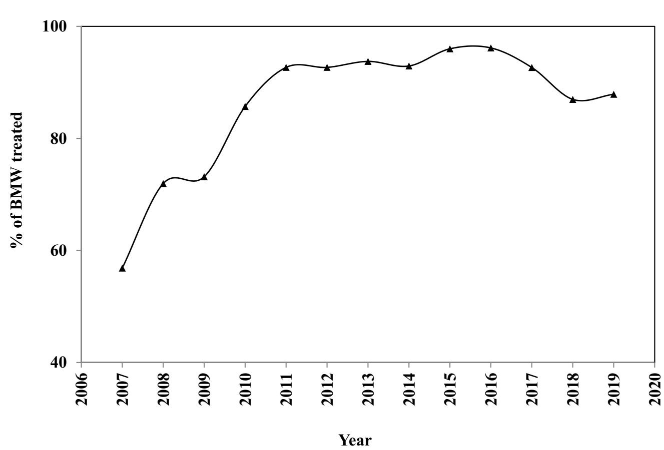

Fig. 2. Percentage of BMW treated in India from the year 2007 to 2019. *Data is collected from CPCB website, 2022.

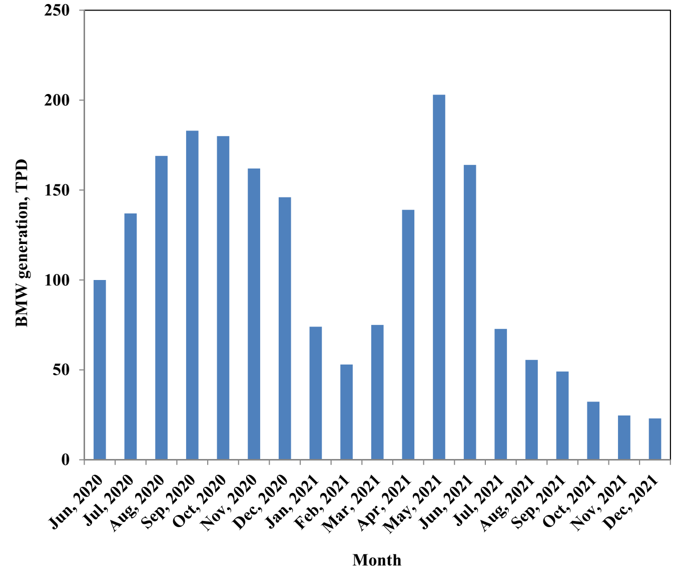

Fig. 3. COVID-19 related BMWs generated in India during pandemic in terms of tons per day(TPD). *Data is collected from CPCB website, 2022.

chemicals. Pharmaceutical wastes like expired and unused drugs are hazardous to the environment as they contain various chemical and radioactive elements. The chemical components present in them are prone to different abnormal chemical reactions in the open environment, which produce next-level toxic chemicals and are too dangerous to the environment (Dehal et al., 2021). There are some cytotoxic drugs used for molecular disorders like DNA damage. They are directly carcinogenic upon direct inhalation and ingestion, so they must be handled with proper care. Other laboratory reagents like solvents and cleaning gels are highly toxic to the environment. Presently a new therapy is developed, which is called nuclear medicines therapy. This therapy uses different radioactive isotopes in the patients. Those patients produce radioactive isotopes in their urine and excreta, which need special attention.

3.2. Non-hazardous BMW

Non-hazardous BMWs include different materials like unconsumed foods, kitchen wastes, cardboards, plastics, thermocol, and papers generated from various hospital activities, subject to the conditions that they are non-contaminated. Unconsumed food and kitchen wastes contribute to the majority of the non-hazardous BMWs. The amount of non-hazardous BMWs is accounted for 75–95% of the total BMWs of a hospital. They are non-toxic and do not need any special attention for the pretreatment before their disposal or reuse. They are generally transported to different treatment systems established for the municipal solid wastes (MSWs) governed by the concerned city or township administrations (Nema et al., 2011). They are used to produce either biogas or manure. Since their amount is much more than the hazardous BMWs, segregation at the source is exclusively considered to minimize the treatment and disposal load. Upon performing the segregation effectively, the overall cost of BMW management can be reduced dramatically (D'Souza et al., 2018).

4. Liquid BMW

Liquid BMWs are generated from different departments and activities of the hospitals like dialysis units, culture and specimen collection centers, chemotherapy units, spinal fluids, blood, by-products of blood, amniotic fluids, and several bodily secretions and fluids. They are collected in the leak-proof containers. They undergo either chemical or autoclave treatment methods to decontaminant before their disposal to the public sewer systems (Chand et al., 2021). Both the treatment methods should be standardized according to the specification of the liquid BMWs. Handling of the liquid BMWs needs skillful workers. Thereby proper training and knowledge are required by the concerned people working in the treatment facilities set up for the liquid BMWs. There are typically three stages involved in the liquid BMW treatment (Biswal, 2013). The standard treatment procedure of the liquid BMW is shown in Fig. 4.

4.1. Primary treatment

All the settleable and floating materials like solid and oil matters are removed from the liquid BMWs in the primary treatment method by using different techniques such as screening, coagulation, flocculation, and adsorption. The primary treatment method makes it easy for following secondary and tertiary treatment methods (Parida et al., 2022). It removes 30 to 40% of the total biochemical oxygen demand(BOD) level and up to 80% of the total chemical oxygen demand(COD) level. The remaining liquid surges to the secondary treatment method.

4.2. Secondary treatment

It involves the biological decomposition or activated sludge process (ASP) to decompose different organic compounds present in the primary treated liquid by using either aerobic or anaerobic microbial degradation techniques. In addition to the ASP, other processes like a constructed wetland, membrane bioreactor, and moving bed biofilm reactor are used to remove both BOD and COD present in the residual effluent of the primary treatment process (Parida et al., 2022). The BOD and COD removal efficiency reaches up to 95% of the total BOD and COD after the completion of primary and secondary treatment processes. The thick slurry/sludge undergoes the gravity settlement resulting in the clear water being passed on to the tertiary treatment.

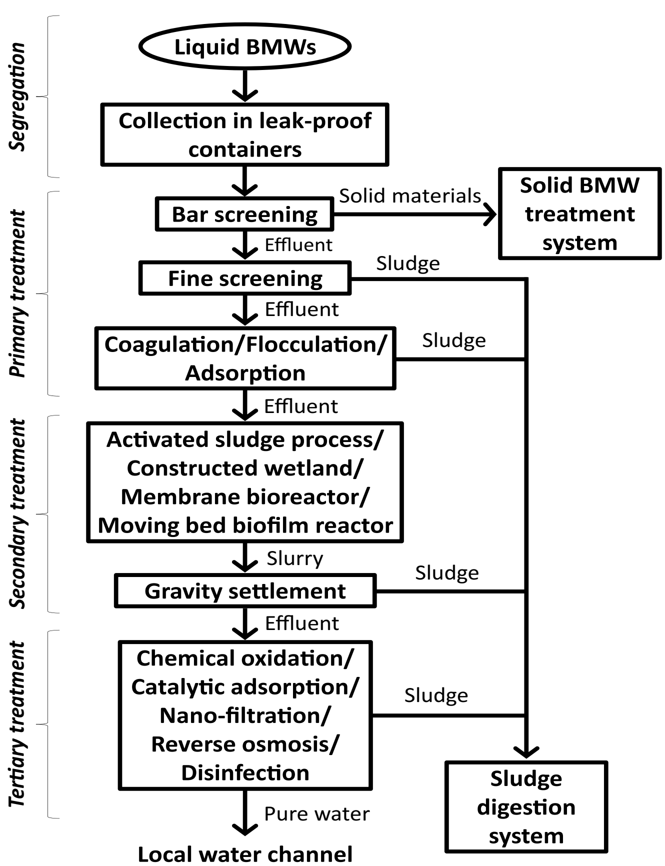

Fig. 4. Liquid BMW treatment procedure (Kaushal et al., 2022).

4.3. Tertiary treatment

The effluent of the secondary treatment process undergoes different advanced treatment techniques like chemical oxidation, catalytic adsorption, nano-filtration, reverse osmosis, and disinfection in order to remove different pathogens, ionic species, and organic compounds. (Parida et al., 2022). In the disinfection technique, the effluent is mixed with sodium hypochlorite solutions and then passed through a dual media filter and activated carbon filter. Similarly, other techniques have their horizon of processing details that are not incorporated. The pure water is released to the local channels for various purposes like recovering underground water levels, irrigation, laundry, toilets, etc.

5. Segregation method for BMWs

Segregation of the BMWs at different entry points is a strategic management policy which reduces its management cost dramatically (D'Souza et al., 2018). An effective and accurate segregation method is necessary for better results. The accuracy of segregation results in the easiness of the final treatment and disposal process. Improper segregation method leads to different adverse effects on the health sectors as well as the increased cost of BMW management (Capoor and Parida, 2021). Therefore, regular training and updated education should be given to the workers related to the segregation process. Further, the workers involved in the segregation process need to follow the strict safety protocol as they are directly exposed to the diverse group of BMWs. Many hospitals have their own set up to segregate at the entry point of BMWs. For simplifying the segregation process, classification of the BMWs is done by different color codes such as yellow, red, blue, black, and white. Different trash boxes are placed in the hospitals according to the color codes in order to execute the segregation at the point of entry. Hospital staffs, patients, and their attendants are sufficiently instructed by the pictorial form to use the specific box for putting the BMWs according to their color codes (CPCB, 2020). Willingness to follow the instructions does a lot of work, especially for the people of developing countries like India. The color codes of different BMWs are given in Table 1. However, the complete outcome of this method is yet to be achieved in developing countries including India (Nema et al., 2011). Upon inefficient segregation at the entry points, ultimately the hospital establishments use the additional workers and time in order to segregate the BMWs at the collection points, which is definitely a cost-borne load. However, performing the segregation at the entry points is the priority over the segregation at the collection points and more focus should be given to achieve the complete execution of the former technique (Ara et al., 2022).

6. Location of treatment facilities

The distance between hospitals and their treatment facilities is an important factor in the BMW management. The segregated BMWs are generally transported to the treatment facilities in different labeled bags with the help of trolleys or BMW transit trucks. Transportation by dragging the filled BMW bags is strictly prohibited. If the distance is more, it takes a long time to reach the destinations. Durable transportation leads to the possibility of tearing of the baggage, which in turn produces a bad smell as well as a small mass loss through the route without knowledge of the vehicle drivers (Nema et al., 2011). Therefore, BMW treatment facilities should be set up at a suitable location near the hospitals. Transportation can be further optimized by the computer-based algorithm for the quick and errorless carriers of the BMWs (Agrawal et al., 2021). However, the hi-tech method can be applied upon intensive practical testing.

7. BMW disposal techniques

Appropriate disposal techniques need to be implemented based on the properties of BMWs that are collected and segregated. Different conventional and alternative technologies are practiced in India for the treatment

Table 1
Segregation and treatment methods for BMWs (Behera, 2021; Dehal et al., 2021; Nema et al., 2011).

BMW Category	Type of Bags/Boxes	Types of BMW	Treatment/ Disposal Techniques
Yellow	Non-chlorinated plastic or semi plastic	• Human anatomical wastes (human tissues, organs, body parts) • Used masks (triple layer masks, N95 masks) • Head covers/caps • Shoe covers • Disposable linen gown • Disposable PPE kits • Tissues and toiletries of COVID-19 patients • Microbial culture • Waste from biological cell culture • Agar petri dishes • Live attenuated vaccine • Swabs contaminated with blood or body fluids of COVID-19 patients including used beds, syringes and medicines	• Plasma pyrolysis • Incineration • Deep burials after autoclaved
Red	Non chlorinated and autoclavable	• Cytotoxic materials • PPEs goggles • Face-shields • Splash proof aprons • Hazmat suits • Nitrile gloves • Viral transport media • Intravenous tubes • Catheters • Urine bags • Plastic vials • Vacutainers • Eppendorf tubes • Plastic cryovials • Oxygen mask	• UV sterilization • Autoclaving • Hydroplaning • Sterilized wastes may be reused or disposed
Blue	Cardboard containers	• Discarded glass and metallic wastes • Tube lights, CFL&LED lights • Glass bottles • Slides • Metallic implants	• Disinfection/Sterilization/Chemical disinfection • Followed by recycling
White	Leak and puncture proof containers	• Waste metallic sharps • Syringes with fixed needles • Needles from needle tip cutter or burner • Scalpels • Blades • Scissor • Burner	• Wet or dry heat sterilization • Sterilized wastes need to be shredded/ encapsulated and then sent for land fill
Black	Non-Chlorinated plastic or semi plastic	• Hazardous wastes • Discarded medicines and cytotoxic drugs • Nicotine • Bulk powders • Expired and unused pills • Hazardous pharmaceutical wastes • Outdated, contaminated, discarded drugs • Used containers of disinfectant and pesticides • Incineration ash • Chemical wastes	• Incineration/destruction and disposal in land fills

of BMWs. Fig. 5 shows the process flow of the conventional BMW Management.

7.1. Steam treatment or autoclave technique

Autoclave technique is an efficient process to disinfect various BMWs. It utilizes high temperature and pressure to sterilize the infected BMWs (Yaman, 2020). But it is suitable for a small amount of BMWs generated in different nursing homes. It requires less time. It generates high-efficiency particulate air (HEPA) which should be filtered at the overhead vents. The disinfection is optimized when the autoclaves run at a condition of pressure between 1540 and 2280 mmHg, temperature 121 °C, and time 30 min (Ilyas et al., 2020). The proficiency of every autoclave cycle relies on time stacking of configuration and packing density, load size, the integrity of packet, temperature, pressure, process sequence, physical and chemical properties of BMWs, and residual air. It is a familiar technique and does not need an expert to run this process. The hazardous BMWs are generally treated by the autoclave technique prior to their disposal. The BMWs undergo this process can be reused, but shredding of materials during the process make them unusable (Yaman, 2020). It is an eco-friendly process and its operating cost is less; however, its installation cost is expensive. It produces toxic effluents, which is a major drawback of its application. It is not suitable for chemical and pharmaceutical wastes as autoclaving these wastes produces unpleasant odour and toxic fumes.

7.2. Microwave treatment

Medium heat microwave technique uses reverse polymerization and thermal depolymerization methods and operates between 200 and 1600 °C (Capoor and Bhowmik, 2017). It uses high-energy microwaves to

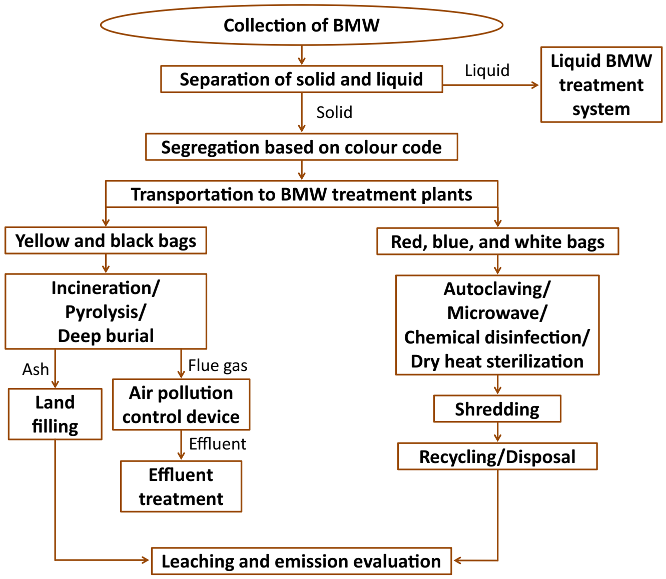

Fig. 5. Schematic conventional techniques used for BMW Management.

the BMWs in the nitrogen atmosphere in order to break down the organic substances. The electromagnetic waves which lie in the wavelength range of 1 mm to 1 m and the frequency range of 100 to 3000 MHz are used to increase the internal energy of the BMW materials. Then chemical decomposition of the activated BMWs takes place at the molecular level due to the rubbing and vibration of molecules (Datta et al., 2018). Nitrogen gas provides an oxygen-free environment in order to prevent the combustion. The microwave devices are specially designed under constraint methods to deactivate the COVID-19 virus efficiently. Additionally, the microwave technology can be used only for sterilization instead of decomposition of the BMWs while running at the lower temperature range. The sterilized BMWs are further shredded for valuable reuse. Mobile microwave treatment facilities can be created, which is highly beneficial for the onsite treatment of BMWs. The mobile microwave has more importance during the pandemic as it can be used at different remote location quarantine facilities that are temporarily set up for the isolation of COVID-19 patients. Since it runs at the lower temperature range for sterilization, its operating cost is dramatically less compared to that of the autoclave technique. It is an eco-friendly technique as it does not produce any by-product or emission. But there is a possibility that the toxic remains of the chemical waste can contaminate the environment upon landfill. Sometimes it produces a bad odour in the surrounding of its operation.

7.3. Dry-heat treatment

The dry heat technique is used for sterilization. It uses very high temperature to kill bacterial spores and microbes. It is generally used for handling a small volume of BMWs. It is used on dry items like glasswares, metal equipment, paper-wrapped items, powders, oil, etc. In this technique, moisture-free high-temperature air is used over a lengthened period for the sterilization of BMWs (Datta et al., 2018). A lot of heat input is required in this process as it uses the conduction, convection, and thermal radiation method of heating (Yaman, 2020). It is an eco-friendly as well as an inexpensive process. It is a non-corrosive treatment process suitable for metals and sharp objects; however, it cannot be used for plastic or rubber items as there is a possibility of damaging these items due to exposure to heat over a prolonged period. Therefore, both temperature and time should be optimized to minimize the volatile organic carbon released from the plastic BMWs during the dry heat treatment.

7.4. Chemical treatment

Chemical treatment is a disinfection technique used for the pretreatment of COVID-19 related BMWs. Chemical disinfectants like Chlorine(Cl_2), Sodium hypochlorite (NaOCl), Chlorine dioxide(ClO_2), Ozone (O_3), and UV irradiation are generally used in this process (Wang et al., 2020). This process is conducted in a covered system for a fixed period so that all pathogens and organic substances are effectively inactivated. The possibility of chemical aerosol formation during the process is minimized by using the high-efficiency particulate absolute filters. The major disadvantage of the process is that it releases large-scale Cl_2 gas into the environment. Both residue and effluent of the process should be analyzed and disposed of with proper regulation. Also, it generates toxic effluent which requires further treatment resulting in the high expenditure of the overall process. Combining the process with a mechanical shredder is used for the complete disposal of BMWs. It is a simple disinfection technique, but the BMWs should be properly shredded before they undergo the chemical disinfection.

7.5. Incineration

Incineration is a common practice and widely used process for the treatment of BMWs. All hospitals have mandatory set up of an incinerator. It is conducted between 800 and 1200 °C in the presence of sufficient air for the complete obliteration of pathogens and organic wastes, which reduces the BMW volume and mass up to 90 and 75%, respectively (Gautam et al., 2010). The aerated burning process generates flue gas containing different toxins like furan and dioxins. Therefore, it needs a secondary treatment plant or a high-quality flue gas cleaning system in order to mitigate air pollution. Also, the ash generated from the incinerators should be properly characterized before its disposal following the statutory regulations. Incineration is a high energy-intensive treatment process and combined with the secondary treatment plant for the toxins makes the overall process expensive. However, its high efficiency for the BMW treatment makes it the most suitable and widely adopted process by different countries. According to the CPCB reports, there are 232 incinerator plants available in India for the treatment of BMWs (CPCB, 2019). Incinerator ash is generally inert towards chemical reactions; however, its direct applications create a problem due to the environmental leaching ability (Kumar et al., 2021; Rajor et al., 2012). The incineration process produces a huge volume of ash which contains heavy metals and inorganic salts (Idris and Saed, 2002). There is a risk of environmental leaching capacity of different metals and ions that further contaminant the groundwater upon disposed of as landfill (Zhao et al., 2009). The toxic byproducts of the incinerators can be minimized by the combined effect of the efficient segregation system, combustion efficiency of the incinerators, and high-quality flue gas scrubber (Kumar et al., 2021). Alternative methods have been applied for the utilization of its value as concrete, cement mortars, road and asphalt pavements, and agriculture. The environmental leachability of metals and ions is reduced significantly by modifying the raw ash. Since incinerator ash is chemically inert, it must undergo chemical activation or surface area modification before applying in the product developments (Rajor et al., 2012). Therefore, evaluation of the ash accurately is necessary before using them in some applications.

7.6. Encapsulation and inertization

This is exclusively a disposal technique that can only be executed after the complete disinfection of the BMWs. In this process, the raw BMWs are ground or broken into small chunks with the help of a crusher machine and then disinfected (Singhal et al., 2017). The disinfected chunks are stared in metallic drums followed by shielding with the plastic foam and then disposed of as the landfill. This technique is adopted only when there is no other physical or alternate method available for the disposal. This is practiced for the small volume of BMWs. The equipment and operation cost are simple and less, respectively. This technique is often used during the pandemic period when the daily BMW generation exceeds the capacity of treatment facilities. During the pandemic, many countries have used this ad-hoc technique for the emergency management of the huge COVID-19 related BMWs. Although encapsulation is simple to execute, it is considered an outdated technique.

7.7. Pyrolysis

Pyrolysis is a more efficient technique compared to incineration. It operates at a temperature range between 540 and 830 °C that is much lower than the incineration (Kaushal et al., 2022). This technique includes plasma pyrolysis, induction-based pyrolysis, pyrolysis oxidation, and laser-based Pyrolysis (Datta et al., 2018). Pyrolysed oxidation is the mechanism used in this technique. The pyrolysed oxidation of different solid and liquid BMWs takes place inside a pyrolysis chamber run at approximately 600 °C. The gaseous vapour formed inside the chamber completely destroys the poisonous substance like dioxins and furans, and clean exhaust steam is released. Therefore, this technique is supposed to be the advanced decomposition method over the normal gaseous combustion. The mass reduction in pyrolysis can be achieved up to 95% (Kaushal et al., 2022). Residues like ash, glass, and metallic fragments are further treated through combustion (Capoor and Bhowmik, 2017). Pyrolysis is an effective method for the BMW management as the emission rate and mass reduction are too low and high, respectively. The clean exhaust steam released in the process is known as *syn*-gas which can further be used indigenously to produce electricity and other fermentation purposes. The generation of electricity from the syn-gas can able to reproduce the electricity up to 31% of that used for the plasma pyrolysis operation (Paulino et al., 2020). The exact thermodynamics of the pyrolysed gas must be evaluated for the regeneration of electricity. Although the initial setup of the plant needs extra cost, it has many advantages over other conventional BMW treatment processes.

7.8. Sanitary landfill

Sanitary landfill is a simple and inexpensive disposal method for disposal of the BMWs. It can be conducted in the existing municipal waste management system. It is the traditional landfill technique and completely banned because of its environmental concern which includes the decomposition of waste resulting in the production of landfills leachate and greenhouse gases (Manzoor and Sharma, 2019). This method can only be adopted if there are no acceptable means of treating the waste before disposal. Few things are considered before the landfill that the site should be geographically isolated and away from the water stream, the operation is managed by a competent authority, and there is an acceptable limit to the quantity that can be landfilled at a location.

7.9. Shredding

In this process, a shredder is used to cut the pre-treated BMWs into small chunks. The shredders should be operated by a competent staff. Shredders are generally built-in devices to the integrated chemical or thermal disinfection system (Gautam et al., 2010). This technique facilitates the recycling of plastics and significantly reduces the volume of BMWs. Metallic wastes should be avoided in the shredders as they can damage the metal blade on them.

8. Developing valuable products

Although there is a negative thought for the re-utilization of BMWs, some research groups have started developing new products from them (Kaur et al., 2019; Mohan et al., 2022; Patil et al., 2019a). Different personal protection equipment(PPE) kits are widely used in health care facilities. The COVID-19 pandemic has augmented their usage resulting in the elevated amount of BMWs (CPCB, 2020). They are generally disposed of by following state-of-the-art treatment methods. But few researchers have applied the used PPE kits as an additive to the construction materials for enhancing the properties (Kaur et al., 2019). The composite construction materials have been developed by mixing the shredded PPE kits with two different types of sand, such as river sand and manufactured sand, in three different filler ratios. The mechano-chemical properties like tensile strength, compression, flexural strength, acid resistance, and moisture absorption capacity of the as developed composites are compared with the existing construction materials and found to be suitable for the construction applications (Kaur et al., 2019; Mohan et al., 2022). Organic BMWs are suitable feed materials for the production of biofertilizers upon decomposing by different natural microorganisms or plant extracts. Some bacteria and fungus isolated from the cow dung have been evaluated for the effective decontamination of pathogens followed by the decomposition of organic BMWs to produce the biofertilizers (Patil et al., 2019a). The plant extracts of *Azadirachta indica* and *Nicotiana tabacum* are found to be effective for the removal of environmental parameters like TDS, BOD, and COD present in the organic BMWs. Upon mixing the residues with soil, Patil et al. have found the superior fertilizer properties in the soil (Patil et al., 2019b). Vermicomposting using the earthworm *Eisenia fetida* has a major advantage in the utilization of the incinerator ash generated from BMWs (Sohal et al., 2021). The vermicomposting system can reduce the heavy metal content as well as increase the fertilizer quality for direct application in the agriculture sector. Composting of the BMWs has a lot of scopes for the production of biofertilizers, which can indeed contribute to the cost reduction of expensive organic farming.

9. Future perspectives

The COVID-19 pandemic may be over by the end of 2022, but we need to be ready for a possible massive pandemic in the future. During the ongoing pandemic, the BMWs from different hospitals are quantified accurately, but the household wastes from different home isolation places confuse the generation of exact mass and volume of the infectious BMWs (Capoor and Parida, 2021). So, there is a need for proper guidelines to quantify the BMWs generated from both hospitals and infected households for lessening the spread of COVID-19 and other viral diseases. The timely collection of wastes from the infected houses without other household wastes is very important. Local administrations should have a close eye and be vigilant about the matter. Proper care must be taken for the complete separation and frequent collection of the infected wastes from the houses (Behera, 2021). This action has an indirect effect on minimizing the COVID-19 related BMWs. The small thing makes a huge impact. Throwing the used face masks and tissue papers here and there is a common and unhygienic practice in developing countries like India. Therefore, an adequate number of special yellow boxes with proper labelling must be fixed at different public places for the disposal of the face masks and tissue papers used for sneezing and coughing by the general public. Also, automatic sanitizer machines should be fixed at different markets and crowded places. The training and education regarding handling the BMWs are generally provided to the health care workers. This education should be implemented in the local communities and schools as one of the co-curricular activities for educating both adults and children. Pictorial information about the handling of infectious wastes at different places may effectively help in the awareness among different groups of people.

The new treatment techniques like heat, chemicals, a combination of heat and chemicals, and irradiation have great potential for the BMW management (EPRI, 2000). These new techniques can address the underlying problems in the conventional BMW management by minimizing pollution, reducing toxin formation, and efficient volume reduction. Advanced techniques like plasma pyrolysis, sharp/needle blaster technology, PIWS-3000 technology, microwave treatment, alkaline hydrolysis, steam sterilization, and biological treatment emerge as the potential candidate for the new age BMW management (Nema and Ganeshprasad, 2002; Raguse et al., 2016). Solar disinfection enters into the BMW management in the semiconductor era where solar cook systems can be used for the disinfection/decomposition of the BMWs. However, the efficiency of the solar disinfection system should be further evaluated and standardized (Thakur and Katoch, 2012). Nanomaterials have been developed to decontaminate different solid wastes (Hooshmand et al., 2022). They are used as the photocatalyst for the simultaneous degradation and generation of the dead cancer tissues and the electricity, respectively. The photocatalytic degradation ceases the toxin emission which is the major drawback of the incinerators. But there are only a few reports available for the photocatalytic degradation of different BMWs. Therefore, the focus should be steered towards the photocatalytic degradation for the BMW management. Alkaline hydrolysis is another method where sodium hydroxide can be added to the steam disinfection system for the complete digestion of the BMWs. It is also found to be effective for destroying the prior wastes which are derived from different animals and contain transmissible spongiform encephalopathy like mad cow (Krička et al., 2014). The emergence of a hybrid system like a combination of chemical treatment and advanced steam sterilization coupled with shredding can effectively disinfect and decompose the BMWs. This hybrid system is potentially suitable for the treatment of biological wastes like pathological waste, anatomical parts, etc.

Decontaminating the cancer cells is a challenging task. Fabrication of Ag/AgCl with C3N4 nanostructures has been synthesized and found to be effective for the treatment of highly contagious cancer cells (Padervand and Hajiahmadi, 2022). Similarly, silver doped wollastonite has been synthesized for the in vitro degradation of different cancer cells (Palakurthy et al., 2019). The application of nanomaterials is not studied intensively for the treatment of different hazardous BMWs. Therefore, the development of nanotechnology for BMW management is indeed necessary as "health is wealth".

The hi-tech methods are approaching every segment of the civilization. The internet of things(IoT) based bio-bin has been developed for the smart collection of BMWs at different hospitals (Akila et al., 2021). The proposed bio-bin is a prototype smart device that can immediately inform the sanitizing workers for the quick collection of the BMWs during the pandemic. The quick response reduces the spread of COVID-19 and other infections initiated from different contagious BMWs.

All conventional techniques for the BMW treatment have multiple drawbacks in terms of energy and emissions. The new technologies have overcome the issues related to the drawbacks and shown more efficiency in the BMW management; however, their high-cost plant set up and operation make hindrance for the wider adoption. Therefore, more efforts and investments should be made available towards the optimization of these technologies. The government and industry partners should come forward to support the research related to the optimization and standardization of these processes. Fig. 6 summarizes the possible aspects of BMW management for overcoming challenges due to COVID-19 like pandemic in the future.

In connection with the management policy, the below points may be taken into consideration for the quick and effective disposal of the BMWs in order to lessen the spread of different viral diseases including COVID-19.

- Effective segregation of the BMWs should be given top priority. Complete segregation at the entry points of BMWs can solve the 80% problems associated with the generation of the huge BMWs during any COVID-19 like pandemic. So there must be a shuffling of the standard handling of BMWs i.e. segregation at the entry points followed by collection instead of the existing system of the collection followed by segregation.
- Health care facilities should conduct proper training and awareness programs for their employees at regular intervals.
- The general public should have sound knowledge about the risks of hazardous/infectious BMWs and their effects upon being handled wrongly.
- Training and regulations for the general public should be conducted as community instructions or learning co-curricular at schools that how to discard infectious or hazardous BMWs.
- Regular inspections should be done by agencies like health administrations, pollution control boards, and environmental protection agencies of different federal governments (Shammi et al., 2022).
- Attendants/patients should be sufficiently instructed in a simple way to discard their wastes within the hospital campus.
- Proper safety protocols should be followed by the workers involved in the sanitization and treatment departments while handling the BMWs in order to lessen the environmental hazard or infection spreading as well as their own safety.
- Conventional treatment methods should be evaluated from time to time.
- Upgradation of the conventional treatment methods should be encouraged.
- Research related to the steps involved in BMW management should be supported by the government agencies and the industry partners in order to overcome the challenges associated with the conventional treatment methods.

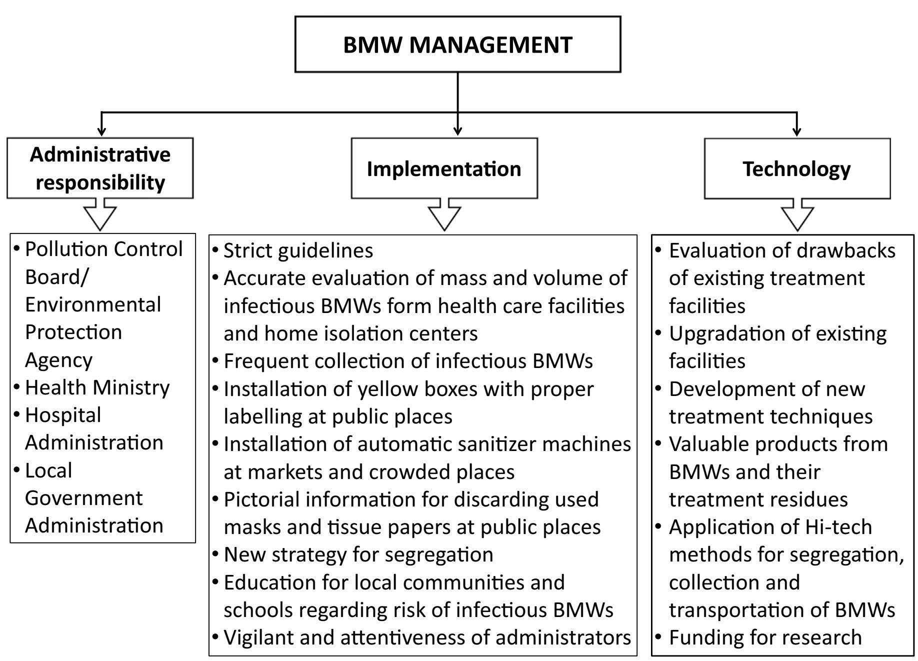

Fig. 6. Possible aspects of BMW management for overcoming challenges due to COVID-19 like pandemic in the future.

- New technology should be developed for the treatment of the flexible amount of BMWs, aiming at the unexpected spike of exploding diseases at a certain period of time just like the COVID-19 pandemic.
- The management body of hospitals should oversee and audit all the policies from time to time as required by the situations and sometimes in a sudden crisis.
- Coordination among hospitals, municipal authorities, treatment providers, and pollution control boards is always given higher priorities for the sustainable and ethical treatment of the BMWs.
- The hospital authorities should take the responsibility of reducing BMW generation in an ethical manner.

10. Conclusion

The daily generation rate of different types of BMWs increases due to the increase of patients as well as the additional guidelines set by the CPCB during the pandemic. India has adequate facilities for the treatment of the enlarged volume of BMWs, but 100% treatment could not be achieved due to the drawbacks of certain policies and guidelines. Segregation of BMWs at the points of entry is very important as a major portion of the BMWs are non-hazardous in nature. Effective segregation can reduce the overall BMW management dramatically. Different conventional treatments techniques have been adopted by different health care facilities worldwide. Still, some techniques need urgent upgradation in order to overcome the disadvantages associated with them. Furthermore, intensive research is required for the development of valuable products from the BMWs. Similarly different new techniques like plasma pyrolysis, sharp/needle blaster technology, PIWS-3000 technology, microwave treatment, alkaline hydrolysis, steam sterilization, and biological treatment should be adopted by sanctioning required funding from the government and the industries partners. Further, some policies should be re-evaluated as the treatment and disposal methods of BMWs adopted by the health care facilities or municipal authorities depend upon numerous parameters like types of wastes, the volume of waste generated daily, the proximity of treatment site to waste source, topological challenges, availability of treatment plants and competent human resources.

CRediT authorship contribution statement

- o Priti Chhanda Ojha: Literature survey; Data interpretation; Writing manuscript
- o Swati Sucharita Satpathy: Writing manuscript
- o Akash Kumar Ojha: Data interpretation
- o Lala Behari Sukla: Writing manuscript
- o Debabrata Pradhan: Data interpretation; Writing manuscript, Overall guidance

Declaration of competing interest

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.

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References

Agrawal, P., Kaur, G., Kolekar, S.S., 2021. Investigation on biomedical waste management of hospitals using cohort intelligence algorithm. Soft Comput. Lett. 3, 100008. https://doi.org/10.1016/j.socl.2020.100008.

Akila, V., Gayathri, B., Avila, J., Thenmozhi, K., Rengarajan, A., Padmapriya, P., 2021. BIOBIN for safe handling and disposing of biomedical waste during COVID '19. International Conference on Computer Communication and Informatics (ICCCI), 2021, pp. 1–4. https://doi.org/10.1109/ICCCI50826.2021.9402682.

Ara, L., Billah, W., Bashar, F., Mahmud, S., Amin, A., Iqbal, R., Rahman, T., Alam, N.H., Sarker, S.A., 2022. Effectiveness of a multi-modal capacity-building initiative for upgrading biomedical waste management practices at healthcare facilities in Bangladesh: a 21st century challenge for developing countries. J. Hosp. Infect. 121, 49–56. https://doi.org/10.1016/j.jhin.2021.11.009.

Behera, B.C., 2021. Challenges in handling COVID-19 waste and its management mechanism: a review. Environ. Nanotechnol. Monit. Manag. 15, 100432. https://doi.org/10.1016/j.enmm.2021.100432.

Biswal, S., 2013. Liquid biomedical waste management: an emerging concern for physicians. Muller J. Med. Sci. Res. 4 (2), 99–106. https://doi.org/10.4103/0975-9727.118238.

Capoor, M.R., Bhowmik, K.T., 2017. Current perspectives on biomedical waste management: rules, conventions and treatment technologies. Indian J. Med. Microbiol. 35 (2), 157–164. https://doi.org/10.4103/ijmm.IJMM_17_138.

Capoor, M.R., Parida, A., 2021. Biomedical waste and solid waste management in the time of covid-19: a comprehensive review of the national and international scenario and guidelines. J. Lab. Physicians 13 (2), 175–182. https://doi.org/10.1055/s-0041-1729132.

Chand, S., Shastry, C.S., Hiremath, S., Joel, J.J., Krishnabhat, C.H., Mateti, U.V., 2021. Updates on biomedical waste management during COVID-19: the indian scenario. Clin. Epidemiol. Glob. Health 11, 100715. https://doi.org/10.1016/j.cegh.2021.100715.

Chowdhury, T., Chowdhury, H., Rahman, M.S., Hossain, N., Ahmed, A., Sait, S.M., 2022. Estimation of the healthcare waste generation during COVID-19 pandemic in Bangladesh. Sci. Total Environ. 811, 152295. https://doi.org/10.1016/j.scitotenv.2021.152295.

CPCB, 2019. Information of common bio-medical waste treatment facilities. https://cpcb.nic.in/uploads/Projects/Bio-Medical-Waste/CBWTF_Status_2019.pdf.

CPCB, 2020. Guidelines for handling, treatment and disposal of waste generated during treatment/diagnosis/quarantine of COVID-19 patients. Revision 4, 17-July-2020. Central Pollution Control Board, Ministry of Environment, Forest & Climate Change, New Delhi. https://cpcb.nic.in/uploads/Projects/Bio-Medical-Waste/BMW-GUIDELINES-COVID_1.pdf.

CPCB website, 2022. Central Pollution Control Board, Ministry of Environment, Forest & Climate Change, New Delhi. https://cpcb.nic.in/. (Accessed 14 March 2022).

Datta, P., Mohi, G.K., Chander, J., 2018. Biomedical waste management in India: critical appraisal. J. Lab. Physicians 10 (1), 6–14. https://doi.org/10.4103/JLP.JLP_89_17.

Dehal, A., Vaidya, A.N., Kumar, A.R., 2021. Biomedical waste generation and management during COVID-19 pandemic in India: challenges and possible management strategies. Environ. Sci. Pollut. Res. Int. 7, 1–16. https://doi.org/10.1007/s11356-021-16736-8.

D'Souza, B.C., Seetharam, A.M., Chandrasekaran, V., Kamath, R., 2018. Comparative analysis of cost of biomedical waste management across varying bed strengths in rural India. Int. J. Healthc. Manag. 11, 38–43. https://doi.org/10.1080/20479700.2017.1289438.

EPRI, 2000. Technical Assistance Manual: State Regulatory Oversight of Medical Waste Treatment Technologies: A Report of the State and Territorial Association on Alternate Treatment Technologies (STAATT). EPRI, Palo Alto, CA 94303 USA, TR-112222.

Gautam, V., Thapar, R., Sharma, M., 2010. Biomedical waste management: incineration vs. environmental safety. IndianJ. Med. Microbiol. 28 (3), 191–192. https://doi.org/10.4103/0255-0857.66465.

Goswami, M., Goswami, P.J., Nautiyal, S., Prakash, S., 2021. Challenges and actions to the environmental management of bio-medical waste during COVID-19 pandemic in India. Heliyon 7 (3), e06313. https://doi.org/10.1016/j.heliyon.2021.e06313.

Hasija, V., Patial, S., Raizada, P., Thakur, S., Singh, P., Hussain, C.M., 2022. The environmental impact of mass coronavirus vaccinations: a point of view on huge COVID-19 vaccine waste across the globe during ongoing vaccine campaigns. Sci. Total Environ. 813, 151881. https://doi.org/10.1016/j.scitotenv.2021.151881.

Hooshmand, S., Kargozar, S., Ghorbani, A., Darroudi, M., Keshavarz, M., Baino, F., Kim, H.W., 2022. Biomedical waste management by using nanophotocatalysts: the need for new options. Materials 13, 3511. https://doi.org/10.3390/ma13163511.

Idris, A., Saed, K., 2002. Characteristics of slag produced from incinerated hospital waste. J. Hazard. Mater. 93, 201–208. https://doi.org/10.1016/S0304-3894(02)00010-9.

Ilyas, S., Srivastava, R.R., Kim, H., 2020. Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management. Sci. Total Environ. 749, 141652. https://doi.org/10.1016/j.scitotenv.2020.141652.

Kaur, H., Siddique, R., Rajor, A., 2019. Influence of incinerated biomedical waste ash on the properties of concrete. Constr. Build. Mater. 226, 428–441. https://doi.org/10.1016/j.conbuildmat.2019.07.239.

Kaushal, R., Rohit, Dhaka, A.K., 2022. A comprehensive review of the application of plasma gasification technology in circumventing the medical waste in a post-COVID-19 scenario. Biomass Convers. Biorefin. https://doi.org/10.1007/s13399-022-02434-z.

Krička, T., Toth, I., Kalambura, S., Jovičić, N., 2014. Efficiency of alkaline hydrolysis method in environment protection. Coll. Antropol. 38 (2), 487–492.

Kumar, A.R., Vaidya, A.N., Singh, I., Ambekar, K., Gurjar, S., Prajapati, A., Kanade, G.S., Hippargi, G., Kale, G., Bodkhe, S., 2021. Leaching characteristics and hazard evaluation of bottom ash generated from common biomedical waste incinerators. J. Environ. Sci. Health A 56, 1069–1079. https://doi.org/10.1080/10934529.2021.1962159.

Manzoor, J., Sharma, M., 2019. Impact of biomedical waste on environment and human health. Environ. Claims J. 31 (4), 311–334. https://doi.org/10.1080/10406026.2019.1619265.

Mohan, H.T., Jayanarayanan, K., Mini, K.M., 2022. A sustainable approach for the utilization of PPE biomedical waste in the construction sector. Eng. Sci. Technol. Int. J. 32, 101060. https://doi.org/10.1016/j.jestch.2021.09.006.

Nema, S.K., Ganeshprasad, K.S., 2002. Plasma pyrolysis of medical waste. Curr. Sci. 83 (3), 271–278.

Nema, A., Pathak, A., Bajaj, P., Singh, H., Kumar, S., 2011. A case study: biomedical waste management practices at city hospital in Himachal Pradesh. Waste Manag. Res. 29 (6), 669–673. https://doi.org/10.1177/0734242X10396753.

Padervand, M., Hajiahmadi, S., 2022. Ag/AgCl@Tubular g-C3N4 nanostructure as an enhanced visible light photocatalyst for the removal of organic dye compounds and biomedical waste under visible light. J. Photochem. Photobiol. A 425, 113700. https://doi.org/10.1016/j.jphotochem.2021.113700.

Palakurthy, S., Azeem, A.P., Reddy, V.K., 2019. In vitro evaluation of silver doped wollastonite synthesized from natural waste for biomedical applications. Ceram. Int. 45, 25044–25051. https://doi.org/10.1016/j.ceramint.2019.03.169.

Parida, V.K., Sikarwar, D., Majumder, A., Gupta, A.K., 2022. An assessment of hospital wastewater and biomedical waste generation, existing legislations, risk assessment, treatment processes, and scenario during COVID-19. J. Environ. Manag. 308, 114609. https://doi.org/10.1016/j.jenvman.2022.114609.

Patil, P.M., Mahamuni, P.P., Abdel-Daim, M.M., Aleya, L., Chougule, R.A., Shadija, P.G., Bohara, R.A., 2019a. Conversion of organic biomedical waste into potential fertilizer using isolated organisms from cow dung for a cleaner environment. Environ. Sci. Pollut. Res. 26, 27897–27904. https://doi.org/10.1007/s11356-019-05795-7.

Patil, P.M., Mahamuni, P.P., Shadija, P.G., Bohara, R.A., 2019b. Conversion of organic biomedical waste into value added product using green approach. Environ. Sci. Pollut. Res. 26, 6696–6705. https://doi.org/10.1007/s11356-018-4001-z.

Paulino, R.F.S., Essiptchouk, A.M., Silveira, J.L., 2020. The use of syngas from biomedical waste plasma gasification systems for electricity production in internal combustion: thermodynamic and economic issues. Energy 199, 117419. https://doi.org/10.1016/j.energy.2020.117419.

Punčochář, M., Ruj, B., Chatterjee, P.K., 2012. Development of process for disposal of plastic waste using plasma pyrolysis technology and option for energy recovery. Procedia Eng. 42, 420–430. https://doi.org/10.1016/j.proeng.2012.07.433.

Raguse, M., Fiebrandt, M., Stapelmann, K., Madela, K., Laue, M., Lackmann, J.W., Thwaite, J.E., Setlow, P., Awakowicz, P., Moeller, R., 2016. Improvement of biological indicators by uniformly distributing bacillus subtilis spores in monolayers to evaluate enhanced spore decontamination technologies. Appl. Environ. Microbiol. 82 (7), 2031–2038. https://doi.org/10.1128/AEM.03934-15.

Rajor, A., Xaxa, M., Mehta, R., Kunal, 2012. An overview on characterization, utilization and leachate analysis of biomedical waste incinerator ash. J. Environ. Manag. 108, 36–41. https://doi.org/10.1016/j.jenvman.2012.04.031.

Richter, A., Ng, K.T.W., Vu, H.L., Kabir, G., 2021. Waste disposal characteristics and data variability in a mid-sized Canadian city during COVID-19. Waste Manag. 122, 49–54. https://doi.org/10.1016/j.wasman.2021.01.004.

Sarkodie, S.A., Owusu, P.A., 2021. Impact of COVID-19 pandemic on waste management. Environ. Dev. Sustain. 23, 7951–7960. https://doi.org/10.1007/s10668-020-00956-y.

Saxena, S., Srivastava, R.K., 2011. Assessment and disposal issues of biomedical waste-case study Allahabad city. Int. J. Biomed. Eng. Technol. 79 (1), 97–104. https://doi.org/10.1504/IJBET.2011.042501.

Shammi, M., Rahman, M.M., Ali, M.L., Khan, A.S.M., Siddique, M.A.B., Ashadudzaman, M., Doza, M.B., Alam, G.M.M., Tareq, S.M., 2022. Application of short and rapid strategic environmental assessment (SEA) for biomedical waste management in Bangladesh. Case Stud. Chem. Environ. Eng. 5, 100177. https://doi.org/10.1016/j.cscee.2021.100177.

Sharma, H.B., Vanapalli, K.R., Cheela, V.R.S., Ranjan, V.P., Jaglan, A.K., Dubey, B., Goel, S., Bhattacharya, J., 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. Resour. Conserv. Recycl. 162, 105052. https://doi.org/10.1016/j.resconrec.2020.105052.

Singhal, L., Tuli, A.K., Gautam, V., 2017. Biomedical waste management guidelines 2016: what's done and what needs to be done. Indian J. Med. Microbiol. 35 (2), 194–198. https://doi.org/10.4103/ijmm.IJMM_17_105.

Sohal, B., Bhat, S.A., Vig, A.P., 2021. Vermiremediation and comparative exploration of physicochemical, growth parameters, nutrients and heavy metals content of biomedical waste ash via ecosystem engineers Eisenia fetida. Ecotoxicol. Environ. Saf. 227, 112891. https://doi.org/10.1016/j.ecoenv.2021.112891.

Thakur, Y., Katoch, S.S., 2012. Emerging technologies in biomedical waste treatment and disposal. Chem. Eng. Trans. 29, 787–792. https://doi.org/10.3303/CET1229132.

Wang, J., Shen, J., Ye, D., Yan, X., Zhang, Y., Yang, W., Li, X., Wang, J., Zhang, L., Pan, L., 2020. Disinfection technology of hospital wastes and wastewater: suggestions for disinfection strategy during coronavirus disease 2019 (COVID-19) pandemic in China. Environ. Pollut. 262, 114665. https://doi.org/10.1016/j.envpol.2020.114665.

Yaman, C., 2020. Application of sterilization process for inactivation of bacillus stearothermophilus in biomedical waste and associated greenhouse gas emissions. Appl. Sci. 10, 5056. https://doi.org/10.3390/app10155056.

Zhao, L., Zhang, F.S., Wang, K., Zhu, J., 2009. Chemical properties of heavy metals in typical hospital waste incinerator ashes in China. Waste Manag. 29, 1114–1121. https://doi.org/10.1016/j.wasman.2008.09.003.