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Can pyrolysis handle biomedical wastes?: Assessing the potential of various biomedical waste treatment technologies in tackling pandemics

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Abstract

Globally, COVID-19 has not only caused tremendous negative health, social and economic impacts, but it has also led to environmental issues such as a massive increase in biomedical waste. The biomedical waste (BMW) was generated from centralized (hospitals, clinics, and research facilities) and extended (quarantine camps, COVID-19 test camps, and quarantined homes) healthcare facilities. Many effects, such as the possibility of infection spread, unlawful dumping/disposal, and an increase in toxic emissions by common BMW treatment facilities, are conjectured because of the rise in waste generation. However, it is also an opportunity to critically analyze the current BMW treatment scenario and implement changes to make the system more economical and environmentally sustainable. In this review, the waste disposal guidelines of the BMW management infrastructure are critically analyzed for many functional parameters to bring out possible applications and limitations of individual interventions. In addition, an investigation was made to select appropriate technology based on the environmental setting.

Keywords: Biomedical waste, COVID-19, Pyrolysis, Waste management, Incineration, Techno-economic analysis.

1. Introduction

The Covid crisis has caused major setbacks to almost all countries across the globe, both morally and financially. Many nations, including developed countries such as the United States, the United Kingdom, the United Arab Emirates, Germany, Italy, Spain, and Romania are still in the process of combating the economic disturbances (Al Hosany et al., 2021; Kalina & Tilley, 2020; P. Kumar & Rasquin, 2020; Mihai, 2020; Ragazzi et al., 2020). The COVID-19 pandemic resulted in a worldwide undersupply of medicines and other protective gear (such as K-N95 masks, face shields, and PPE kits) against the virus. Additionally, COVID-19 has presented a serious environmental threat due to the vast amount of biomedical waste. Alongside generating huge quantities of biomedical waste during the first and second waves, the lack of proper protocols extended the negative impacts to other sectors of modern society, such as global economic instability, mortality rates and unlinking international/domestic supply chains. The advanced healthcare facility initiated temporary hospitals, isolation wards, quarantine camps, quarantine homes and testing centres to deal with the pandemic. However, the mitigation measures taken by the respective governments were also point sources for waste generation. The exponential rise in cases and the colossal quantity of waste generated made waste segregation and storage a challenging task. Moreover, the high transmission rate of the COVID-19 virus among the victims (Gousseff et al., 2020; Sarkar et al., 2020) emphasized that inadequately treated biomedical waste (BMW) can be a potential source of new COVID-19 waves (Singh et al., 2020).

Considering the impact of COVID-19 on human life and subsequent influence on the government's economic policies, focus should be given to understanding potential pathways to recycling and managing waste. Although COVID-19 is an act of the past, neither a dedicated medicine nor a 100% effective vaccine is yet available on the market. Therefore, proper preventive measures and effective BMW management approaches are critical in combating COVID-19 or similar pandemics in the future. In addition, achieving a sustainable solution for treating biomedical waste on the aspect of thermal chemical conversion way for the conversion of waste to valuable sources is essential. This is because a thermochemical conversion of waste could not only be a viable approach for managing waste by emitting very less harmful gases to the environment but also provide a pathway for transforming the waste into wealth while ensuring product application sustainably (Cai and Du, 2021; Dharmaraj et al., 2021). Another advantage is that the thermal process could manage biomedical materials in a higher capacity, in a possible scenario of the pandemic, in an environmentally friendly way. Therefore, in the aspect of biomedical waste, with its diversification of content/inequality, presence of contamination, and other harmful contents, the assessment of existing waste management systems with thermal technologies will be a conventional way of finding a promising solution for the destruction of contaminants/harmful content by converting waste to valuable materials. Subjecting to the recent pandemic (COVID-19) as the case scenario, the current review was intended to find a possible sustainable global solution for handling biomedical waste in day-to-day life and tackling future pandemics.

Therefore, the present review covers critical aspects of waste collection and recycling. In addition, the Indian BMW management system in pre-pandemic and post-pandemic scenarios is highlighted to understand the existing waste management systems. Furthermore, extensive literature analysis was carried out to understand the applicability of potential technologies, such as pyrolysis, for decentralized handling of infectious waste generated from the temporary sources. Finally, pyrolysis was valued against centralized BMW treatment facilities equipped with incinerators. Overall, this review is a comprehensive and systematic approach to understanding BMW guidelines, analyzing existing treatment and disposal of BMW systems, possible thermo-chemical conversion processes for handling biomedical waste, and comparison between them for getting a sustainable technology for tackling future pandemics.

2. BMW treatment guidelines

BMW is generated by a healthcare facility that, if not adequately treated, poses a biochemical risk of infecting humans or contaminating the environment. Anatomical parts, bandages, used syringes, and plastic products used for culture development or medicinal packing can be classified as BMW. For example, since the SARS-CoV-2 virus could remain on the surface and in aerosol particles for up to 72 hours (Saxena et al., 2022; Singh et al., 2020), improper handling of BMW could be considered one of the major reasons for the spread of infection for extended periods. Hence, many countries have established protocols to tackle the problem of BMW management during COVID-19 (Babu et al., 2009). Guidelines from some of the developed/developing countries are summarised in Table 1.

Table 1. Guidelines, plan, and notice associated with COVID-19 waste management (Singh et al., 2022).

Country	Practices for COVID-19 waste generated from healthcare facilities	Reference
USA	(i) Environmental Protection Agency (EPA) has developed interim guidance for public meetings for the Resource Conservation and Recovery Act program during the COVID-19 (ii) EPA has compiled frequent questions about COVID-19 and waste. (iii) EPA has developed an Interim Guidance on Site Field	(World Health Organization, 2020)

	Work Decisions due to the impacts of COVID-19.	
China	(i) Environmental Management of Medical Waste Caused by COVID-19 (EMMW COVID-19), January 2020. (ii) Work Plan for Comprehensive Waste Management in Medical Institutions, February 2020. (iii) Notice on the Management of Medical Waste in Medical Institutions for COVID-19, January 2020. (iv) Guide on Management and Technical on Emergency Treatment and Disposal of Medical Waste Caused by COVID-19, January 2020.	(Ma et al., 2020)
India	(i) Guidelines for Handling, Treatment, and Disposal of Waste Generated during Treatment/Diagnosis/Quarantine of COVID-19 Patients were issued by the Central Pollution Control Board. (ii) Individual State Pollution Control Boards provide more detailed guidelines for concerned stakeholders in their respective states.	(CPCB, 2020)
UK	(i) Guidelines titled COVID-19 waste management standard operating procedure. (ii) Guidelines for waste disposal by DHSC titled “Management and disposal of healthcare waste” under (HTM 07-01)	(Department for Environment, 2021; Health, 2013)
Japan	(i) Ministry of Environment, Japan (MOEJ) notified all	(Ministry of

		local governments to confirm the existing guidelines and manuals for healthcare waste to manage COVID-19 waste.	the Environment, 2020)
Philippines	(i)	The Republic of the Philippines, Department of Environmental and Natural Resources, Environmental Management Bureau provided a provisional guideline on hazardous waste management during the extended enhanced community quarantine period on 7th April 2020.	(Republic of the Philippines, 2020)
	(ii)	The Republic of the Philippines, Department of Environmental and Natural Resources, Environmental Management Bureau amended interim guidelines on issuing a special permit to transport (SPTT) for the transportation of hazardous wastes within the community quarantine period on 16th March 2020.	
	(iii)	The Republic of the Philippines, Department of Environmental and Natural Resources, Environmental Management Bureau, had provided an addendum to the interim guidelines on issuance of a special permit to transport (SPTT) for the transportation of hazardous wastes within the community quarantine period on 14th March 2020.	
	(iv)	The Republic of the Philippines, Department of Environmental and Natural Resources,	

		Environmental Management Bureau, had provided interim guidelines on issuing the special permit to transport (SPTT) for transporting hazardous waste within the community quarantine period on the 16th March 2020.	
Malaysia	(i)	The clinical waste management services are led by private companies under government supervision under the Environmental Quality (Scheduled Wastes) Regulations 2005 and regulated by the Malaysian Department of Environment (DoE). DoE governs all aspects of clinical waste management, including collection, transportation, treatment, and disposal. It uses an electronic scheduled waste management system to ensure compliance.	(Penta Floras, 2022)
Indonesia	(ii)	National Disaster Control Agency oversees the overall coordination in handling COVID-19-related issues.	(Budihardjo et al., 2022; Tsukiji et al., 2020)
	(iii)	The Ministry of Environment and Forest (MOEF) enacted the following items: (a) Letter #S.167/MENLHK/PSLB3/PLB.3/3/3030 concerning the Handling of HCW in the health facilities in the emergency for COVID-19. (b) A waste generated from COVID-19 handling is classified as hazardous under the GR #101/2014	

	law. (c) A Circular Letter #SE.2/MENLHK/PSLB3/PLB.3/3/2020 for handling infectious and household waste. (d) A special letter from the Directorate General of Waste and Hazardous Waste Management of MOEF sent to a private company of transportation, treatment, and disposal regarding healthcare waste management in emergency conditions covering COVID-19 waste.

The guidelines listed in Table 1 were developed considering each nation's pre-installed BMW treatment facility infrastructure. It was reported in 2018 that India has 198 standard BMW treatment facilities, and 28 are under construction. In addition, ~21,870 healthcare facilities (HCFs) have established treatment units. The total BMW generated from ~1,68869 HCFs in the country is 484 tonnes/day, of which 447 tonnes/day is treated. Out of the total BMW generated, 85% is non-hazardous, and 15% is hazardous, which cannot be directly treated (Datta et al., 2018a). As of January 2021, the amount of BMW generated in India has almost doubled and increased to 775.5 million tonnes/day. The most recent rules for BMW disposal as of March 2020 state that the pre-treatment of laboratory wastes, microbiological wastes, blood samples, and blood bags should be done after disinfection or sterilization (Al Hosany et al., 2021) and a separate record is to be maintained record the details, including collection, treatment and disposal, of COVID-19 waste. The general rules and regulations for handling and treating BMW specific to India are discussed below (Rajak et al., 2022; Aggarwal, 2020)

2.1 Segregation and storage

The medical waste generated (tons/ day) during active COVID-19 pandemic in different countries is shown in Figure 1. Based on the total population and the total number of COVID-19 cases in different countries, India had produced a very high amount of medical waste, i.e., around 6,491.49 tons/day, significantly higher than other countries such as Iran, Pakistan, Saudi Arabia, Bangladesh, Turkey, Iraq, Qatar, Indonesia, Philippines, and China (Sangkham, 2020). Therefore, the amount of medical waste generated was considered as a criteria to further discuss the segregation and storage of biomedical waste. In this context, India was considered as base case scenario and was reviewed thoroughly to create a common platform and understand the possible measures and necessary precautions to be taken if there arise a similar situation in the near future.

In India, waste segregation and storage occur at the source, i.e., HCFs. In terms of disinfection capacity and economics, it is to be noted that waste segregation is necessary as the disposal/sterilization techniques are effective when used for specific materials. Storage and treatment strategies for BMW adopted in India are mentioned in Table 2.

Table 2. Colour coding and type of container for disposal of BMW (Ministry of Environment and Forests, n.d.).

Colour Code	Type of Container	Waste Category	Type of waste	Treatment option
Yellow	Plastic Bag	• Human anatomical waste • Animal wastes • Microbiology and biotechnology waste • Soiled wastes	• Human/Animal Tissues, organs, body parts • Soiled bedding/ robes etc. • Microbe culture	Incineration Temperature: ~900°C (primary) ~1000°C (secondary)
Red	Disinfected containers/plastic bags	• Microbiology and biotechnology wastes • Soiled wastes (body fluids, cotton, dressing, soiled plaster casts, linens, items contaminated with blood)	• Microbe cultures/research specimens, attenuated vaccines, etc. • Soiled cotton, bedding, casts, and robes.	Autoclaving 120°C, 15 psi (60 min) 140°C, 31 psi (45 min) 150°C, 52 psi (30 min) Microwave
Blue/white	Plastic	• Waste sharps	• Needles, syringes,	Autoclaving

translucent	bag/puncture-proof container	• Solid waste (wastes generated from disposable items other than the waste sharps such as tubing catheters, intravenous sets, etc.	scalpels, blades, glass. • Tubing, catheters, IV sets, etc.	120°C, 15 psi (60 min) 140°C, 31 psi (45 min) 150°C, 52 psi (30 min) Microwave
Black	Plastic bag	• Discarded medicines and cytotoxic drugs • Incineration ash • Chemical waste (solid)	• Outdated, contaminated, or discarded drugs • Chemical disinfectant • Ash from incinerators	Disposal in a designated landfill

Currently, medical waste that has contacted the carrier of Coronavirus or SARS-CoV-2 in any form is discarded in yellow bags and sent for direct incineration without any segregation, mainly to avoid the chances of spreading an infection. Other than COVID-19 waste, red bags include contaminated recyclable wastes from disposable items such as tubing, bottles, syringes, intravenous tubes, sets, syringes with and without needles, gloves, etc. Translucent white boxes are used for discarding sharps like needles, scissors, scalpel blades, etc. Blue boxes are used for discarding contaminated glassware. During the COVID-19 pandemic, BMW generation increased from 447 tonnes/day (Datta et al., 2018a) to 775.5 tonnes/day (Sogi and Sudan, 2019). Most of the BMW was generated in Maharashtra (17.5 tonnes/day), Gujarat (11.7 tonnes/day), Delhi (11.1 tonnes/day), Tamil Nadu (10.4 tonnes/day), and Madhya Pradesh (7.5 tonnes/day) (Chand et al., 2021). Waste segregated at HCFs is stored as a part of the overall COVID-19 waste management protocol (Yang et al., 2020). According to the guidelines, it is recommended that the waste should not be held for more than 24 h (Revision, 2020) because the COVID-19 waste still has a risk of infecting the handling staff for up to 72 h. Figure 2 shows the persistence period of coronavirus on different waste surfaces.

In instances where the volume of waste production has exceeded disposal capacity of the system, on-site construction of a pit for waste burial during an emergency was suggested (Chartier, 2014). The pit acts as a buffer and avoided the overloading of the waste management infrastructure. The waste can be stored for 15-20 days to allow for natural disinfection of the waste material until it is safe and convenient to handle. In addition, such pits are designed with cemented covers and a soil dome to avoid air contamination. The interior surface is also layered with an earth mound to prevent groundwater contamination, where the waste is placed layer-over-layering (Ali et al., 2017).

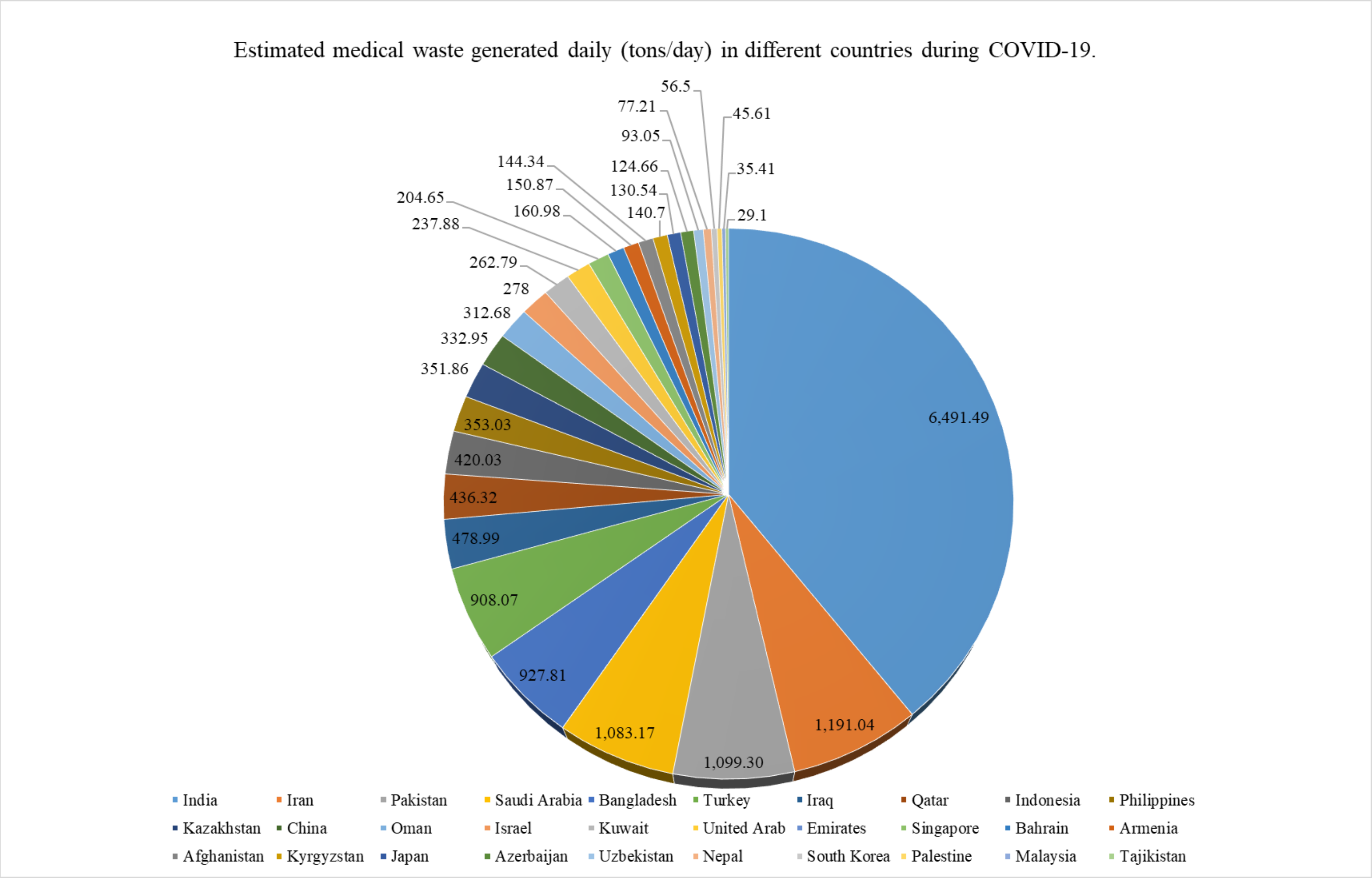

Figure 1. Estimated medical waste generated daily (tons/day) in different countries during COVID-19 (Sangkham, 2020).

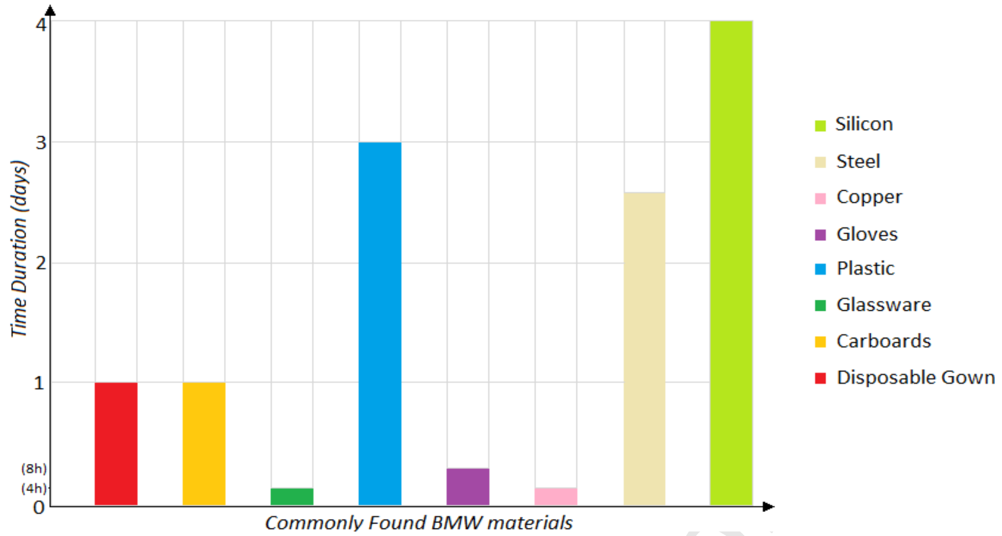

Figure 2. Persistence period of corona virus on different waste surfaces (Kampf et al., 2020).

2.2 Collection and transportation

Globally, biomedical waste is classified into three major types: hazardous, non-hazardous, and other wastes (shown in Figure 3). Each class and subclass under biomedical waste may have a varied level of contamination and associated hazards. Hence, utmost care is needed in the handling and management of biomedical waste. Proper procedures need to be defined prior to the collection of biomedical waste in any country to determine its infection potential. For example, standard procedures defined by the Environment Protection Authority (EPA) in Australia simplifies the collection of clinical and related waste. The defined steps include separating the packing and labelling of waste, training the staff in handling waste, employing licensed contractors to collect and transport waste, using the EPA portal to make sure the disposal facility has a license to treat clinical and related waste, and reviewing the processes in regular intervals (South Australia EPA, 2021). Similarly, in China, a set of defined procedures are employed for the collection and transportation of biomedical waste from village clinics in rural China (Gao et al., 2022). It has also been noticed that Chinese policy makers and health advisory committees need to have more emphasis on rural areas in addressing potentially hazardous medical waste for adequate collection and transportation (Gao et al., 2022). In addition to the above, India, which is the largest populated country, follows certain guidelines for the systematic collection and transportation of biomedical wastes.

According to the International Pollutant Elimination Network, India, in-house transportation of BMW is considered a key performance indicator of the efficiency of BMW's management system (Kumar et al., 2019). It is recommended that the BMW movement in-house and transportation to the facility vehicle should be done in a sealed trolley and should never be moved directly by hand. The working staff should also wear PPE as a further precaution against contamination (Mihai, 2020). It is to be noted that waste from HCFs should be collected and stored at a site 500 m away from HCFs. In India, BMW is transported from the HCFs to a centralized collection area in the same complex by wheeled trolleys with lids handled by a BMW management staff. The staff members are also instructed to wear personal protective equipment (PPE) to avoid microbial contact by any means. The waste is transported to an on-site or a centralized joint facility for waste treatment via a van. The van should have a separate closed chamber for waste storage to avoid exposing the driver and staff member during the transportation phase (Mission, 2016).

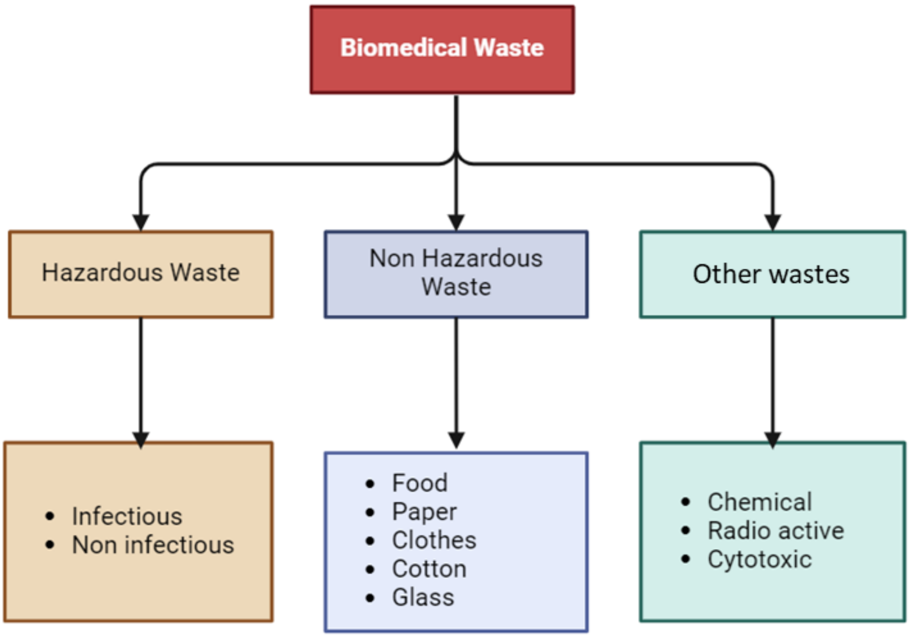

Figure 3. Schematic classification of biomedical waste (Kaushal et al., 2024).

2.3 Treatment and disposal

The treatment and disposal of waste are highly dependent on the constituent materials of the waste. The following section elaborates on properly identifying BMW and the possible treatment methods.

2.3.1 BMW compositions

PPE: The main aim of PPE during pandemics like COVID-19 is to minimize the scattering of large respiratory droplets that may contain the SARS-CoV-2 virus. Though a considerable variety of equipment comes under the category, a few key components and their composition are presented in Figure 4.

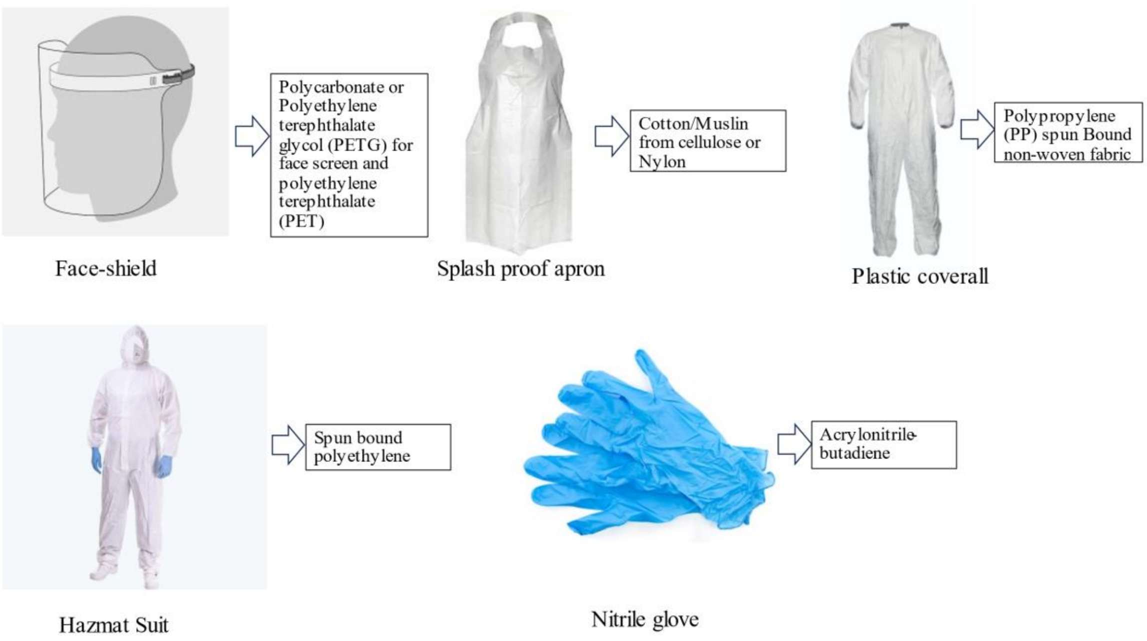

Figure 4. Key PPE and their compositions.

Masks: These include triple-layer masks, N95 masks, etc. Since the size of a coronavirus particle is about 120 nm, N95 masks were the most used. It is flat folded and expands into a convex-shaped mask with the following components: polyamide/spandex elastic head-loops to secure the mask to the user's face, a malleable aluminium strip positioned above the nose for a tighter seal around the nose and face. The respirator comprises four layers of material: (i) an outer layer of spun-bond polypropylene (PP), (ii) second layer of cellulose/polyester, (iii) third layer of melt-blown polypropylene filter material, and (iv) fourth layer of spun-bound PP (Hutten, 2007).

Headcover/cap: Surgical caps are a part of medical protective clothing and should prevent germs from the hair or scalp of surgical personnel from contaminating the operating area. Single-use head covers/caps are made of non-woven PP fabric.

Shoe-cover: Made of a similar material to surgical caps, which helps avoid contamination or carrying pathogens to or from patient wards.

Disposable linen gown/bed sheet & pillow covers: Surgical linen gowns are made of superabsorbent cotton (refined and mercerized cellulose) and are the outermost layer of protection for a surgeon. Hospital bedding covers are made of cellulose.

Tissue papers and cotton swabs: Tissue papers are composed of cellulose.

Medical test kits: Glass screens and PP body/dropper (Lantos, 1987).

The BMW construction material is disposed of via two major methods: (i) non-incineration and (ii) incineration methods (Congress, 1990). The non-incineration methods include autoclaves, mechanical/chemical treatment, microwave treatment, irradiation, and plasma pyrolysis. Incineration is the most common and widely used technology as it reduces the waste volume by 80%, which can be safely discarded in landfills.

2.3.2 Treatment of BMW

From the current study's perspective, BMW treatment is categorized into different types, such as incineration, autoclave, mechanical/chemical treatment, microwave treatment, irradiation, and plasma pyrolysis as briefly discussed below.

Incineration is a thermal treatment technique that has been successfully utilized for a long time (implementation of BMW incinerators boomed since the 1990s (Datta et al., 2018b)) to reduce the volume of solid waste (Kuo et al., 2008). Incineration converts waste into ash producing flue gas and heat as by-products (Mattiello et al., 2013). The organics are converted into gases at high temperatures (Niessen, 2010) (about 1200^{o}C), and the inorganics retained in the incinerators (ash) are discarded onto the landfill. Modern incinerators have filters to trap the ash from exiting through the flue gases. Moreover, the enormous heat generated can be utilized to produce electricity (Kuo et al., 2008).

Incineration is one of the most preferred options for BMW disposal due to their advantages, including (i) the ability to handle all forms of infectious and most chemical and pharmaceutical wastes, (ii) very high disinfection efficiency, (iii) drastic reduction in weight and volume of waste, (iv) high processing capacity, (v) low residence time, (vi) production of heat and energy, (vii) provision for trapping pollutants, (viii) provides better control over odor and noise, and (ix) autonomous/computerized monitoring system. However, inefficiencies that limit their application include the emission of dioxins (Vilavert et al., 2015) and furans from polychlorinated materials, toxic metals in the ash (Maître et al., 2003), and inorganic emissions. For these reasons, developed countries like Denmark have banned the use of incinerators in solid waste management (Gentil et al., 2009). Table 3 summarizes the quantitative information of incinerators employed in the healthcare waste management sector in respective countries, including the number of incinerators installed and operating.

Table 3: Available incinerators for healthcare waste management in respective countries [98].

Country	Total number of incinerators	Number of incinerators operating
Bangladesh	5	3
India	225	Not available
Indonesia	110	Not available
Kenya	10	Not available
Malaysia	12	12
Mexico	19	Not available
Saint Lucia	20	0
South Africa	9	9
Thailand	78	78

Autoclaves are generally recognized as sterilizing equipment. Autoclaves can be considered as BMW handling equipment rather than as disposal technologies. It uses heat and pressure to sterilize the medical equipment (Hossain et al., 2012). In addition, they can be used as an alternative to incineration (Ferdowsi et al., 2013) at the source of BMW generation, particularly when the product can be reused after sterilization (Hossain et al., 2011). In this method, wastes are sterilized or disinfected before being considered for reuse or disposal in a landfill. Waste bags are placed in a chamber, and steam is introduced for a specified time at a specified pressure and temperature (Hossain et al., 2012); (Ferdowsi et al., 2013) assuring microorganisms' destruction. Approximately 90% of regulated medical wastes are suitable for autoclaving, particularly microbiological wastes (Khan et al., 2019). Autoclaves are unsuitable for pathological, cytotoxic, or other toxic chemical wastes. The above advantages also come with several setbacks. One of the main problems associated with autoclaves is that the process can aerosolize chemicals in the waste (Dai et al., 2016), posing a hazard to workers operating the facility and, to some extent, to the environment. These aerosols can get deposited on surfaces in ductwork or countertops and floors. Moreover, unlike incinerators, these have limited options for waste treatment. For example, heavy-duty containers, bedding material, and bulky items cannot be disinfected in an autoclave, and there is no volume reduction (Emmanuel et al., 2001).

Mechanical and chemical treatments are generally used to reduce the volume of the waste, and to disinfect the waste, respectively. Both these techniques are often coupled to produce the best results (Wang et al., 2020). Mechanical systems can increase the surface area of the solid pieces before subsequent chemical or heat treatment (Ilyas et al., 2020). Commonly used chemical disinfectants for BMW are ethylene oxide (due to its low temperature of action and sterilization over a wide range of microbial activity) (Hutmacher et al., 1996), polyacrylic acid solution (for its low-temperature sterilization and higher penetration) (Clapp et al., 1994), ethanol (for its lower cost of treatment and normal anti-microbial activity conditions) (Huebsch et al., 2005) and iodine (for effective sterilization at ambient temperature) (Block, 2001). The problems associated with mechanical treatment are dust generation, regular maintenance of mechanical equipment, and constant sanitization and disinfection (Al-Khatib et al., 2009). Chemical treatment is highly suited for liquid waste that is disinfected and sent to the effluent treatment plants (Biswal, 2013). Mechanical and chemical treatment are batch processes and require a specified amount of time for completion. If the waste includes solids, mechanical treatment, such as milling and shredding is needed for size reduction of the solids to increase the surface area for effective chemical treatment. After treatment with the liquid disinfectant, the solids are filtered out, and the liquid filtrate goes to the sewer for additional treatment.

Microwave treatment is generally used for sludge treatment (Graczyk et al., 2007). These units can have on-site installations or can also be mobile units. The general operation takes place at about 2450 ± 20 MHz (Vela & Wu, 1979). The treatment works only when a microwave absorber, such as water, is present in the waste because radiation transfers only through water, not solids. It is one of the best treatments for disinfection as it eradicates around 99.99% of pathogens. Moreover, it is economically advantageous compared to incineration and offers greater control over the inactivation process while minimizing energy and water consumption. Microwave technology has a high capital cost compared to other technologies and is not easily scalable for large installations (Zimmermann, 2017). The technology also offers localized instead of homogenous heating; hence, treatment time increases.

Irradiation treatment technique makes use of gamma radiation for the treatment of waste. The electron beam (EB) sterilization process relies on the DNA/RNA and pathogenic microbial inhibiting action of ionizing radiation (Tata & Beone, 1995). The gamma radiations are generated using a cobalt-60 source to destroy the pathogens present in the waste (Marchioni et al., 1992). Some irradiation treatment systems use electron beams. Both gamma rays and electron beams can penetrate plastic bags used for waste collection, so the waste does not need to be separated from the bag for treatment. Irradiation requires a dedicated place, and mobile units cannot be made. Moreover, the operation requires a skilled workforce, and radiation is harmful if exposed (Subramaniyan, 2018). The cost of using this facility is also high and accumulates costs in terms of licenses and maintenance fees. The technology also has low public and social acceptance and misconceptions (Machi & Iyer, 1994).

Plasma pyrolysis process is designed and developed for metallurgical processing and material synthesis. This process has been extended for the treatment of plastic waste. Plasma pyrolysis is a thermal process that uses extremely high temperatures to generate plasma in an inert environment to convert waste to syngas (Nema & Ganeshprasad, 2002). The hot gases generated through plasma pyrolysis are quenched through water scrubbing to avoid recombination reactions of gaseous molecules. The plasma is generated by connecting the graphite electrodes to a high-current source (Paradisi et al., 2019). The syngas generated contain combustible hydrocarbon gases such as ethylene, acetylene, carbon monoxide, and hydrogen. The process is not fully used to dispose of medical waste, but it is a feasible and likely option. Figure 5 presents a compact description encompassing various waste disposal processes via the techniques discussed. Different approaches to treat BMW depending on the type of waste and employed technologies is pictorially presented in Figure 5. It is worth noting that Figure 5 presents a broad classification of biomedical waste. In addition, the defined technologies are beneficial for handling and managing biomedical waste; however, certain disadvantages are associated with each technology based on product gas emission, solid residue after treatment, and operation/treatment conditions. Table 4 presents an overview of the applications and limitations of each technology that may help decide while selecting an appropriate technology for a given type of waste, its quantity, and its impact on the environment.

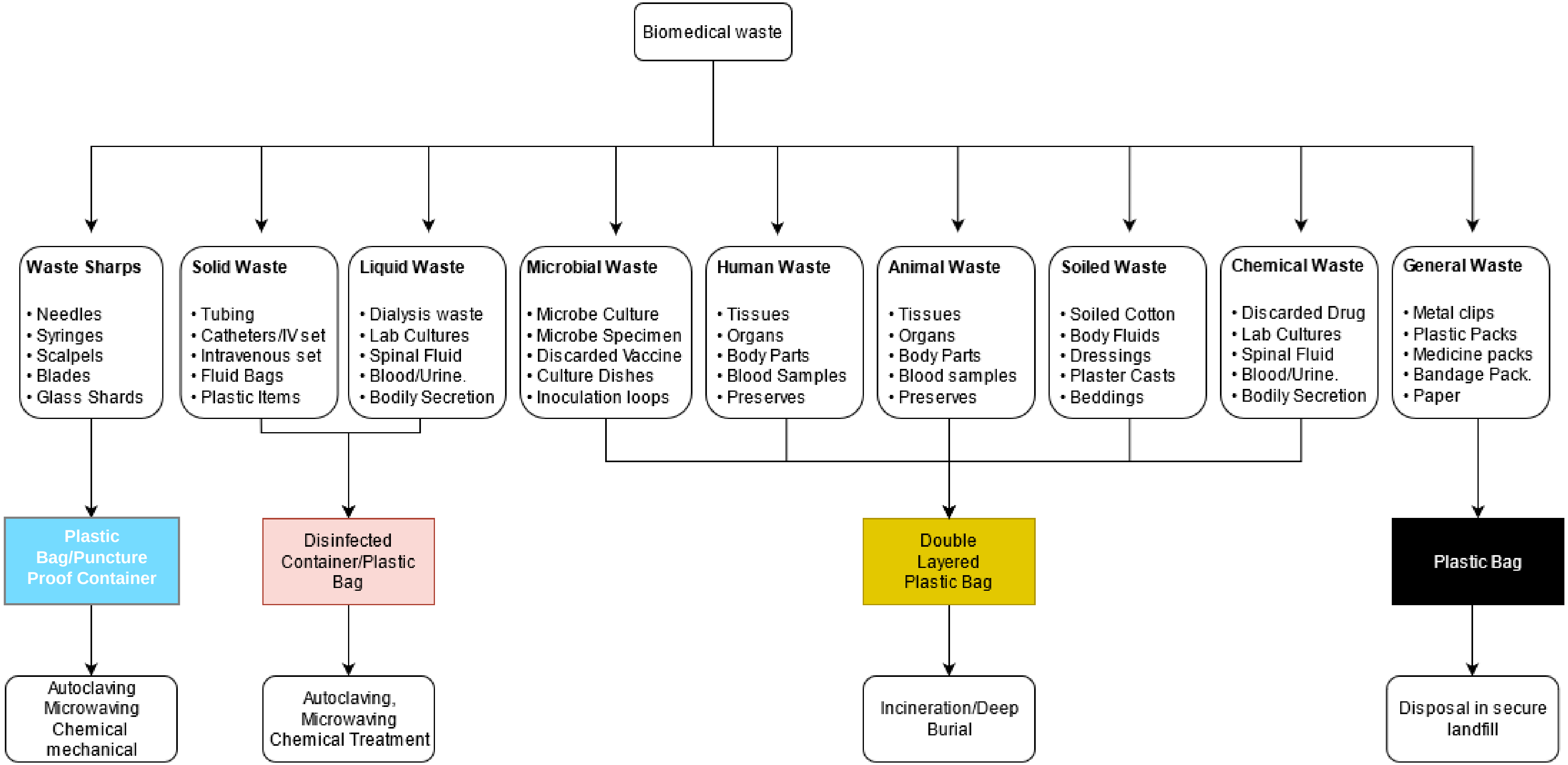

Figure 5. BMW treatment flowchart

Table 4. Different technologies used for BMW treatment.

Type of treatment	Ease of operation	Requirement of shredding	Pre-treatment	Operating temperature (°C)	Scalability	Pros	Cons	Types of reactors	Environment friendly	Ref
Incineration	Easy	Yes	No	800-1400	Easily Scalable	The volume of the waste was reduced to around 80% waste sterilization reducing the need for pre-processing of waste	Plastic waste produces dioxins and furans when burnt directly; It has fine particles that include heavy metals; Production of acid gases, ozone, ash, and a large amount of heat; Ash is highly toxic that contains hazards from the waste	Multiple hearth type; Rotary kiln; Controlled air type	No	(Niessen, 2010)

Autoclave treatment	Easy	Shredding with compression	It is a pre-treatment technique	121-132	Difficult to scale up	They can be a substitute for incineration	Aerosol formation of the gases emitted from the waste; Can efficiently work in batches and not continuously; Require sufficient pre-set cycle time required for heating and cooling, which cannot be modified	A simple batch autoclave with steam inlet; High pressure or high vacuum process	Produces less gas compared to incinerators	(Armstrong & Reinhardt, 2010)
Mechanical/ Chemical Disinfection	Easy	It is used to change the physical nature of the waste	It is a pre-treatment technique	100	Yes	Reduction of the bulk volume of waste by 60%; Chemical disinfection is most appropriate for liquid wastes; Mechanical processes increase the surface area required for proper chemical disinfection	Cannot kill pathogens or disinfect wastes; Dust generation through mechanical treatment	Mechanical equipment like shredders, grinders, pulverizers, and crushers; chemical disinfectants include chlorine and ethylene oxide	Depending upon the treatment	(Niessen, 2010)

Microwave	Easy	Yes	No	100	Yes	Works best for wet feed;New processes designed for working without water	Works best when there is water in the waste; Requirement of a humidifier	Vacuum or under pressure	Yes	(Zimmermann, 2018)
Irradiation	Difficult	Yes	It is a pre-treatment technique for disinfection	NA		Eliminates almost 99.99% of the bacteria	Waste surfaces facing the radiation source get more sterile than the waste on the shaded side; Odd-shaped pieces may not get adequate exposure to radiation	Use of gamma radiations	Yes	(Thakur & Katocha, 2012)
Plasma Pyrolysis	Easy	Yes	No	1200	Yes	Environmentally friendly; Medical waste is pyrolyzed into CO_2, H_2, and other hydrocarbons	The technology must be fully developed to be commercially used for waste treatment.	Fixed bed, fluidised bed reactors	Yes	(Punčochář et al., 2012)

3. Problems with BMW management in India: pre-/post-COVID-19 scenarios

India's BMW management guidelines have been designed with the assumption of an idealistic implementation in the practical case. However, such an ideal execution is not practically possible due to the severe lack of funds directed toward waste management in general (Datta et al., 2018a). Though several other factors contribute to the improper management of medical waste in India, most spawn from the lack of expendable resources. These were strained further due to the massive amounts of garbage produced during COVID-19. It is noteworthy that these problems existed before COVID-19 as reported by several studies (Gahlot et al., 2019; Manasi et al., 2014; Mathur et al., 2012). The COVID-19 pandemic accelerated the compounding effect of the situation. As per recent statistics, it has been estimated that an average Indian hospital produced about 1.5 kg/person of medical waste post-lockdown period (Venkataraman, 2020).

Furthermore, hospitals were required to pay large sums of money for disposing of bio-waste amid the coronavirus pandemic. The cost of BMW disposal, which was INR 24 per kg before the lockdown increased to INR 50 for handling COVID-19 bio-waste ever since the lockdown came into effect. Moreover, hospitals also paid a supplementary charge, at an average, of INR 500 per trip for collecting COVID-19 bio-waste. The lockdown period saw this charge rise to INR 750. As a result of the rising charges, several instances of unlawful dumping have been encountered throughout the pandemic (The New India Express, 2020; World Health Organization, 2022). The current system could be more effective at reducing the produced waste to ash without generating toxic gases, which are expensive to separate via incineration stack. Since managing the waste cheaply is economically desirable, reports of ragpickers being hired at common BMW treatment facilities for waste segregation without

PPE became a concern. Such problems can be tackled by introducing the “source-to-waste” treatment.

4. Incineration versus pyrolysis technology

Statistically, an average Indian hospital produces a minimum of ~100kg/day of BMW (Pandey et al., 2016). Considering ~170,000 (Haque et al., 2018) treatment centres operating nationwide, the total waste generation would be ~17,000 tonnes/day. On an annual basis, about 6,205000 TPY (tonnes per year) of BMW is produced domestically. The treatment equipment has different capital and operating costs depending on the nature of the operations and fuel utilization. Large-scale incinerators require electricity and fuel to maintain the temperature and reduce the gases. They can handle vast quantities of solid waste. It is estimated that 5-7 tonnes of solid waste are required to have the equivalent of 1 tonne of fuel oil, which means a considerable amount of fuel oil is required to burn the waste (Energies, n.d.). Alternatively, if electricity is used for operating the incinerators, the final energy obtained from the waste can be converted into electricity, which may be profitably compared to fuel utilization and conversion. Incineration is the most favoured option because of its versatility in feeding handling. Conventionally, managing and treating waste is manageable and solvable when the waste is indistinguishably treated. According to Chen et al. (2013), the ash produced in a high-temperature incineration unit indicated the availability of higher percentages of polycyclic aromatic hydrocarbons (PAHs) in the fly ash than the bottom ash. These PAHs were found to be highly carcinogenic and dangerous to the people in the vicinity of the incinerators. The working life of the equipment usually ranges from 15-20 years.

Even though the ash produced in the incinerators is highly carcinogenic, they are the most favoured option to date. A comparative case study between incineration and pyrolysis can explain the usefulness of the latter technology over the conventional system. The pyrolysis plants can be designed to operate in batch or continuous mode, depending upon the need. The batch process requires considerable labour to feed the raw materials and remove the product. However, the continuously operated plants can operate continuously for 4-5 days, conserving the fuel used to heat or thermally degrade the waste (Beston., n.d.; Beston Henan Machinery, n.d.). The continuous plant may require a pre-treatment unit for disinfection and shredding of the wastes. Moreover, the continuously operated plant can be designed for any capacity of feed needed. The feed can include any form of waste that can generate significant energy. The pyrolysis plant can produce electricity and fuel depending upon the capacity, thereby generating profits by utilizing the waste as a resource.

The primary focus of processing BMW is that there should be no/minimum residue in the reactor. Fast pyrolysis can be an option, where the waste is thermally decomposed to produce pyrolysis oils that can be further utilized as a diesel-grade fuel (depending on the nature of feed) or feed to generate specialized chemicals. Also, the non-condensable gases generated can help produce electricity, which can help operate the plant. Similar to incineration, the solids products of pyrolysis consist of carcinogenic PAHs. Recent studies show that the amount of PAHs generated can be significantly reduced by varying some parameters during pyrolysis, like operating temperature, particle size, and residence time (Fang et al. 2020).

In addition to this, the pyrolysis technique has been widely used for the formation of contaminated free biochar from the thermochemical conversion of contaminated waste such as biosolid and municipal solid waste (Hakeem et al., 2022), (Ahmed and Hameed, 2020). This unique feature of thermal destruction of contaminants in waste during thermochemical conversion in an inert atmosphere makes the pyrolysis technology significantly demandable from other thermal technologies and non-thermal waste treatment processes (Elkhalifa et al., 2022). Also, the derived biochar from a pyrolysis process has many functionalization properties that can be potentially used in many applications such as energy storage, catalysts, additives in rubber and construction industries, etc (Oliveira et al., 2017). Therefore, it can be suggested that handling contaminated BMW through pyrolysis would not only be beneficial in destroying the contaminants but also the heterogeneity of BMW would act as a synergistic effect during pyrolysis processes in forming valuable biochar and bio-oil.

5. Techno-economic analysis

The techno-economic analysis of incineration and pyrolysis units are compared based on 2000 tonnes/day of feed. The comparison of overall capital investment and the operating cost reported in this analysis is based on the literature data. The currency is converted to million INR/annum, and the inflation rates were considered for the calculations. A rough comparison of the economic data for the thermal pyrolysis and incineration technologies ascertains that the initial investment cost for the same capacity is higher for a bubbling fluidized bed operated at a temperature of 500^{o}C, as presented in Table 5. However, it is observed that the operating cost is considerably lower for the pyrolysis unit. Besides, out of the total electricity produced, almost 80% is utilized by the pyrolysis plant, which has a liquid fraction suitable to generate value-added chemicals (Ringer et al., 2006). The crude oil generated can provide more remuneration than the electricity produced in the process by considering the separation cost of the substances involved. Overall, the use of pyrolysis technology is not only a cost-effective approach, but also the product generated (oil and biochar) from the process has a high-value application in forming chemical and other industrial aspects.

Table 5. Economic comparison between thermal pyrolysis and incineration (Al Hosany et al., 2021)

Type of Process	Plant Cap (MT/day)	Cap. Investment (MM INR-PY)	Op. Cost (MM INR-PY)	Initial ROR (%)	Fuel-derived (TPY)	Electricity Produced (MkW/Year)	References
Incineration	2000	2832.8	2573.9	8	Not applicable	233.33	(Ye et al., 2019)
	274	4832.71	596.44	13	Not applicable	46.71MWh/Year	(Schneider et al., 2010)
	0.6	3578.79	21.43	4.59	Not applicable	48375000KWh/Year	(Rezaei et al., 2018)
	3565.5	9146.22	365.65	9.68	Not applicable	386905.76MWh/year	(Escamilla-García et al., 2020)
Pyrolysis	2000	8929.1	904.02	10	4,68,097	5.92	(M. Haque et al., 2018)
	40	283.56	16.29	10	7395.738 m^3/year	Recovery options are available but not quantified explicitly	(Ghodrat et al., 2019)
	24	944.13	391.005	35.97	749		(Ghodrat et al., 2019)
	140	791.95	226.20	21.7	26		(Westerhout, n.d.)

In order to justify the observation made in Table 5, a critical analysis was conducted on different technologies, i.e., incineration, pyrolysis, gasification, and hydrothermal carbonization, as tabulated in Table 6. Four critical parameters, including CAPEX, operational, and maintenance (O&M) costs, and high-value-added products and market value were considered and compared against each technology. From Table 6, it can be noticed that the CAPEX and O&M costs for pyrolysis and incineration are relatively low compared to gasification. Although the cost of incineration is close to pyrolysis, the market value of the products obtained from incineration is low. On the other side, the market value of pyrolysis products, including biochar, bio-oil, and combustible gases, is significantly high. In addition, emerging technologies such as hydrothermal carbonization could be a promising alternative technology for bio-medical waste management. However, to the best of the author’s knowledge, information regarding capital and operating costs for hydrothermal treatment technologies is currently unavailable. Overall, it can be stated that in the current scenario, pyrolysis is a promising technology for handling bio-medical waste in a sustainable and cost-effective way.

Table 6. General relative comparison of different thermal technologies for bio-medical waste treatment

Parameter	Incineration	Pyrolysis	Gasification	Hydrothermal Carbonization
CAPEX (INR per kg)	1251-2086 (Aleluia and Ferrão, 2017)	1000-2200 (Riedewald et al., 2021)	1300-65888 (Elwan and Habibuddin, 2021)	Information regarding pilot-scale or demonstration-scale hydrothermal facilities is currently unavailable in the literature. A few Lab-scale studies have been done so far. (Ardhistira et al., 2020; Shen et al., 2017)
O&M costs (INR per kg)	10- 24 (Aleluia and Ferrão, 2017)	21 (Lubongo et al., 2022)s	41 (Elwan and Habibuddin, 2021)	No information available in the literature
Product	• Residual ash and fly ash (from incombustible materials) • Trace organic and inorganic compounds in the exhaust gases. • CO_2 and water vapour	• Biochar • Combustible product gases • Bio-oil	• Residual ash (after complete gasification) • Partly gasified biochar • Syngas	• Hydro char • Aqueous (rich in nutrients) • Product gases
Market value	**Low:** Only the residual ash can be used for other consumption applications (e.g., construction material), depending on its properties.	**High:** Biochar has diversified applications in both thermal and non-thermal processes, such as solid fuel, catalyst, adsorbent, agricultural, and construction. Combustible gases can be used for heat recovery and for fuel for other sub-processes in an integrated pyrolysis plant. Bio-oil has applications in forming valuable chemicals and other processes like carbon sequestration.	**Medium**: Residue ash and partially gasified biochar can be used for different applications based on their properties. Syngas can be used to generate electricity and fuel.	**High:** Hydrochar can be used in different applications, such as energy-related and agricultural. The aqueous phase can be used for agricultural applications. The product can be potentially applied as a heat source in different processes. Also, it can be further processed to get H_2-rich product gas.

6. Conclusions and recommendations

- The treatment of BMW has always been a worldwide concern. Besides, the onset of the pandemic has triggered a dire need for quick and effective waste management. Pyrolysis used in BMW treatment may help contribute to the economy by generating fuel/power from waste.

- Using small pyrolysis units at the source of the BMW generation can help in saving the extra cost that the hospitals bear for waste disposal. Besides, this approach could act as a source of revenue generation by selling the pyrolysis oil produced.
- The literature survey indicates that the product composition is variable because of the different feedstocks used. Since medical waste (and municipal waste, for that matter) is not adequately segregated, as per the norms, processing the waste becomes costly; though developing an advanced pyrolysis system can help to a greater extent, the venture should initially focus on establishing a supply chain and an effective segregation system. By employing a formally structured semi-automated segregation facility, a wide range of waste can be processed by simple, cost-effective techniques like pyrolysis.
- The COVID-19 scenario is one of the situations where a sudden surge in BMW was observed. Suppose we can successfully build up a system wherein the amount of discarded waste can be minimized, and a circular economy is generated by utilizing this waste. In that case, the burden on the centralized system can be reduced, and things can be managed even during unwarranted situations like the current one that the world has witnessed recently.
- According to the Central Pollution Control Board 2022, the BMW that is COVID-19 virus-infected should be eliminated or treated immediately [100]. Therefore, processing BMW with a low energy footprint and reducing or eliminating the hazardous gases from these wastes needs careful consideration to efficiently handle similar pandemics in the future [101] .

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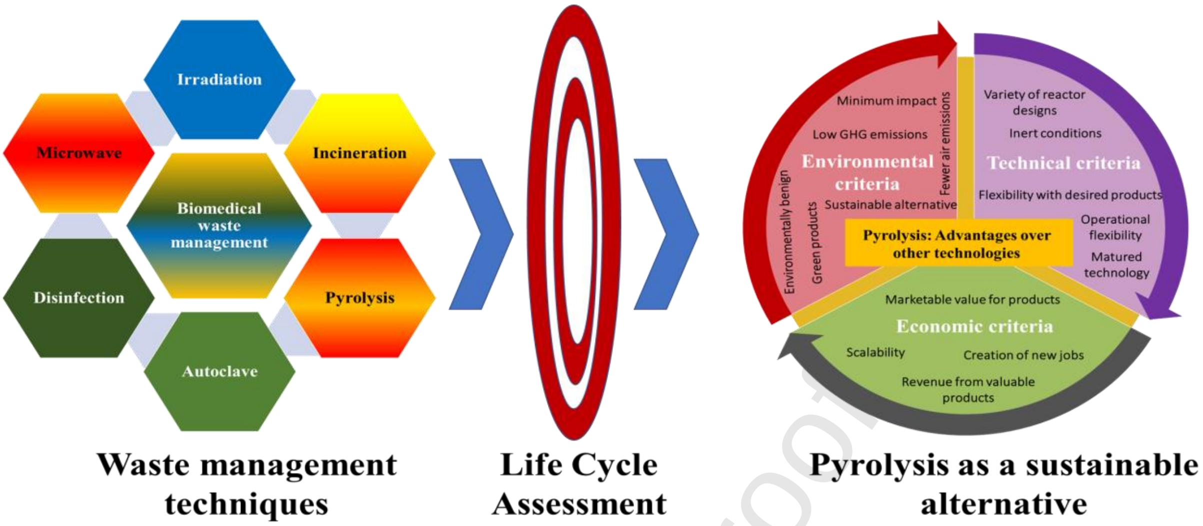
Declaration of Interest

All authors agree to their participation in this manuscript preparation and All authors also disclose that there is no financial and personal relationships with other people or organizations and no conflict of interest amongst the authors or organisations involved in this manuscript.

Graphical abstract



Highlights

- Unattended biomedical waste is a techno-economic and socio-environmental burden.

- Pyrolysis of biomedical waste contributes to sustainable energy production.

- Decentralized handling of biomedical wastes via pyrolysis is cost-effective.

- Life cycle assessment highlights pyrolysis as a sustainable conversion technology.