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Chapter- 5

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Current Landscape and Future Perspectives of Biomedical Waste Management in India

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Keywords: Biomedical Waste Management, Nosocomial infection, BMWM in India, CBWTF, SWOT analysis.

Abstract:

Biomedical waste management (BMWM) is a crucial aspect of healthcare operations, encompassing the entire process from waste generation to its treatment and disposal. This paper provides an in-depth analysis of the present state of BMWM in different states of India, highlighting variations in Common Biomedical Waste Treatment Facility (CBWTF) utilization. The discussion includes the key initiatives undertaken by the Indian government, emphasizing the Biomedical Waste Management Rules of 2016, which expanded the regulatory framework and responsibilities. Furthermore, it explores various technologies for medical waste management, categorizing them into thermochemical, biochemical, and chemical methods. Thermochemical technologies such as incineration, gasification, pyrolysis, plasma-based methods, carbonization, hydrogenation, and liquefaction are discussed in detail, along with their operational conditions and potential products. The analysis underscores the need for collaborative efforts, technological advancements, and stringent regulations for addressing the challenges in BMWM. Special emphasis has been given to the importance of informed decision-making, SWOT analysis, and tailored waste-to-energy solutions for effective medical waste management in diverse healthcare settings.

Introduction:

Biomedical waste, abbreviated as BMW, is any waste generated as a result of operations such as diagnosing, treating, or immunizing humans or animals, as well as performing research

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and creating or testing biological compounds. From start to finish, the process requires a complete strategy that involves evaluating, measuring, separating, storing, transporting, and treating. The 3Rs philosophy is at the heart of successful BMW management (BMWM). Prioritizing waste avoidance and recovery above simply disposing of trash is a critical component of achieving successful BMWM. BMW disposal strategies are ordered hierarchically, with prevention being the ideal method, followed by reduction, reuse, recycling, recovery, treatment, and disposal. This emphasizes the need to address waste from its source rather than relying on a reactive "end-of-pipe" technique. A BMW treatment and disposal facility is a particular location where the complicated operations involved in BMW (biomedical waste) treatment, disposal, or management take place (Chartier et al., 2014). A key issue to note is that just a tiny fraction of BMW (biomedical waste) is classified as hazardous. This offers several threats to both the general public and healthcare personnel engaged in waste disposal, including physical, chemical, and microbial hazards. The vast majority, 75%–95%, is categorized as non-hazardous (Li, 1993). A key World Health Organization (WHO) meeting held in Geneva in June 2007 agreed on essential principles to support the secure and long-term management of healthcare waste. The urgent necessity for prudent resource allocation and an unwavering commitment to limiting the negative impacts of healthcare waste on both people and the environment were emphasized. Stakeholders involved in financing and supporting healthcare operations have a moral and legal obligation to pay for the costs associated with effective BMW management. Manufacturers must build environmentally friendly medical devices that can be safely disposed of. The WHO emphasized the need for governments to contribute a portion of their resources to the development, support, and maintenance of effective healthcare waste management systems that embrace modern methods and technology to reduce waste bulk and toxicity. Non-governmental organizations are strongly encouraged to undertake projects and activities that contribute to this overarching goal (Salkin et al., 2004). A previous study estimated that around half of the world's population is at risk from inadequate biomedical waste management (BMWM), jeopardizing either their work environment or public health. The ubiquitous occurrence of public health risks caused by inaccurate BMWM has been thoroughly established (Harhay et al., 2009). Instances such as the hepatitis B virus (HBV) pandemic in Gujarat, India, in 2009, with 240 documented infections, and the occurrence of infectious injuries among scavengers as a result of Afghanistan's massive immunization campaign (1.6 million) are particularly noteworthy (Chartier et al., 2014). The International Clinical Epidemiology Network conducted a major statewide review of 25 districts in 20 states, highlighting the inadequacies of BMWM systems across India. Only two major cities, Chennai and Mumbai, demonstrated much greater BMWM practices. The main issues were related to inadequate biological waste processing at the source and ineffective terminal disposal methods. According to the survey, approximately 82% of primary, 60% of secondary, and 54% of tertiary care health institutions were rated as "red," indicating either a lack of a credible BMWM system or an urgent need for significant improvement (Gadicherla et al., 2016).

Further supporting these findings, World Health Organization (WHO) surveys in 22 developing countries revealed that the proportion of healthcare facilities (HCF) without appropriate waste disposal systems ranged from 18% to 64% (Kumari et al., 2013). In India alone, around 0.33 million tons of biomedical waste are generated each year, with rates ranging from 0.5 to 2.0 kg per bed per day (Mathur et al., 2011). According to a recent study (David, 2016), bad practices in BMWM are caused by a lack of information and training.

Current Situation of BMWM in Different States of India:

Analyzing the provided data on Biomedical Waste (BMW) management in various Indian states reveals a noteworthy spectrum of circumstances (Costa et al., 2023). There exists a pronounced variability in the utilization of Common Biomedical Waste Treatment Facility (CBWTF) capacities, with percentages ranging from 17% to 86%. This discrepancy underscores disparities in the efficacy of BMW management systems and the facilities' ability to handle the generated waste. Some states, including Arunachal Pradesh, Goa, Mizoram, and Nagaland, lack CBWTFs or possess insufficient capacity, necessitating infrastructure enhancements. Notably, states like Chhattisgarh, Haryana, Maharashtra, and Punjab face challenges with CBWTF capacity utilization below 60%, pointing to potential issues in fully leveraging authorized capacity. Conversely, states like Assam, Jammu Kashmir, Kerala, and Tamil Nadu showcase efficient CBWTF capacity utilization, offering valuable insights for other regions. Although the total authorized CBWTF capacity exceeds the actual BMW generation, certain states may require additional capacity or infrastructure improvements (Figure 1). Addressing these challenges and fostering collaboration between states to share expertise and resources is crucial for cultivating a more cohesive and effective nationwide waste management system.

Initiatives of The Indian Government:

India, a country that has been at the forefront of addressing environmental issues, implemented Biomedical Waste Management (BMWM) laws in 1998. These laws, which came under the 1986 Environment Protection Act (EPA) and were later amended as drafts in 2003 and 2011, marked a significant advancement (Sharma et al., 1998). India ratified the legally binding Stockholm Convention in 2004 to decrease or eliminate persistent organic pollutants (POPs), in addition to its commitment to international environmental accords (Fiedler et al., 2007). By releasing the BMWM regulations in 2016, particularly on March 28, 2016, the Ministry of Framework, Forests, and Climate Change of the Government of India significantly contributed to the development of the regulatory framework. These regulations were deliberately created to fill in the legal gaps left by earlier legislation, using provisions from the EPA, 1986, and provide a comprehensive framework for the managed disposal of different kinds of biological waste (BMW) (Capoor, 2017). The Biomedical Waste Management Rules of 2016 significantly expanded the definition of biomedical waste beyond the traditional definition of healthcare facilities (HCF). This included a wide range of settings, including vacc-

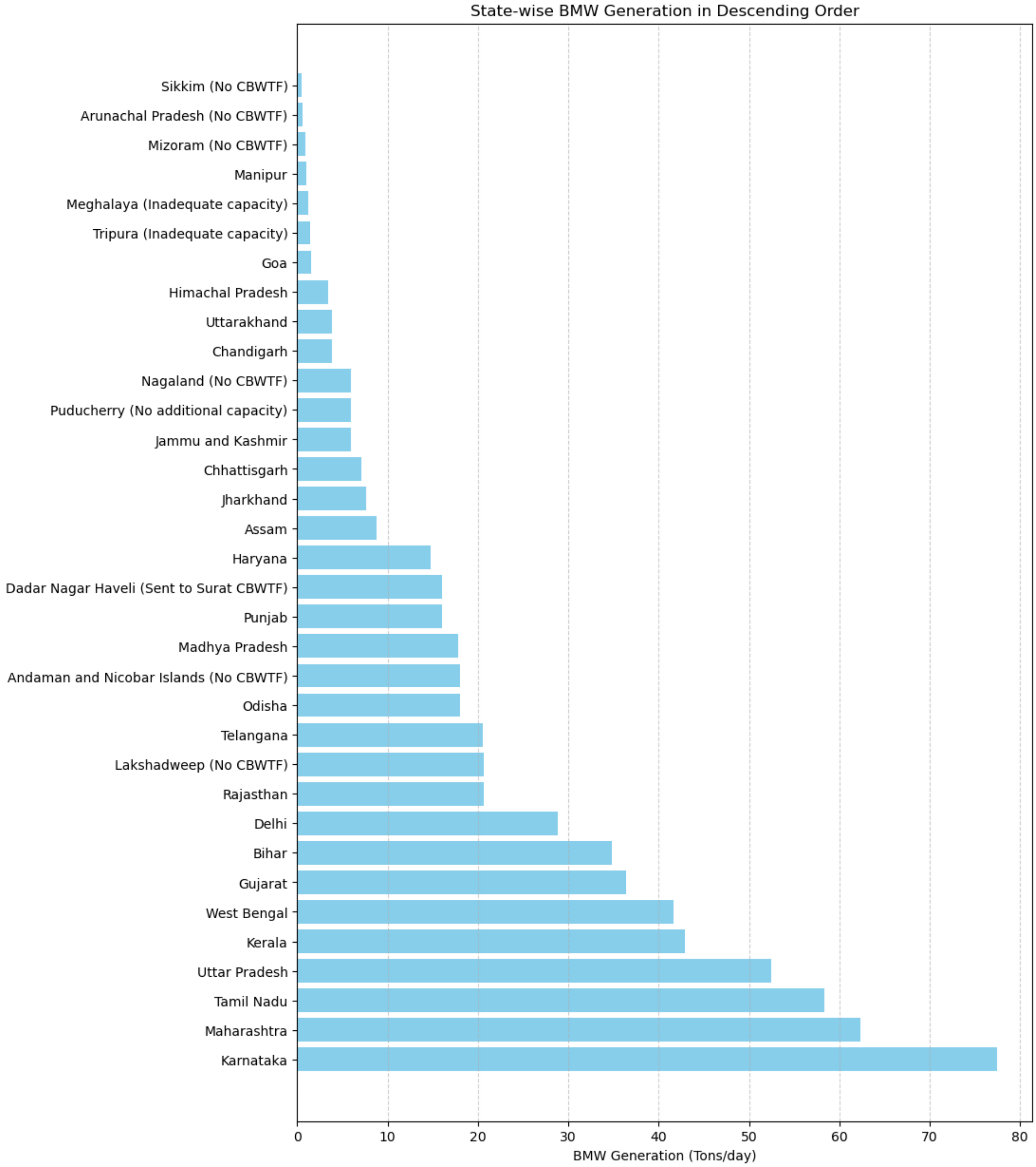

Figure 1: State-wise BMW generation in India.

-ination camps, blood donation camps, school first aid rooms, forensic labs, medical colleges, research laboratories, household biomedical wastes, and any other health-care activities related to various medical systems. To increase responsibility and clarity, the duties and responsibilities of the tenant, the Common Biomedical Waste (CBMW) management disposal facility, and the authorities were all spelled out. The occupier must guarantee the pretreatment of diverse biomedical waste streams, including blood samples, blood bags, microbiological waste, and laboratory garbage. This calls for following the regulations and doing on-site sterilization or disinfection. In addition to picking up trash, the occupier is in charge of offering health-care workers (HCWs) full support services, such as vaccinations, training, and workplace safety. By mandating that major incidents be reported to the relevant authorities and mentioned in the annual report, the guidelines emphasize responsibility and openness. Additionally, the occupier is expected to establish a strong framework for evaluating and overseeing BMWM operations via a dedicated committee. According to certain parts of the Act, both the occupier and the Common Biomedical Waste Treatment and Disposal Facility (CBMWTDF) acknowledge legal responsibility for any environmental or public harm resulting from negligent BMW management. The 2016 BMWM regulations contain criteria for waste disposal pits, effluent management, and other equipment-related standards in addition to these specific operating recommendations. To increase accountability and traceability, the regulations also include the use of barcoding and GPS technology. The company's focus on accident reporting, strict adherence to records, and establishment of a dedicated website connected to BMW is indicative of its dedication to openness and ongoing improvement. The regulations also place a strong emphasis on environmentally sustainable methods for final disposal technologies, promoting the use of green technologies, waste-to-energy solutions, newer technological approaches, plasma pyrolysis, and recycling that is made possible by licensed recyclers.

Technologies For Medical Waste Management:

There are broadly three types of classification for BMWM:

1. Thermochemical technologies
2. Biochemical technologies
3. Chemical technologies

Thermochemical technologies:

Incineration:

Incineration is the primary method for digesting and cleansing medical waste, to reduce both its volume and its risk. This approach produces a significant reduction, exceeding 80% in solid mass and 90% in volume (Shareefdeen et al., 2022). Incineration, which operates at temperatures ranging from 800 to 1450°C, allows for the complete annihilation of combustible components by oxidation processes aided by an abundance of air (Helsen, 2010; Kassim et al., 2022). Waste-to-energy conversion occurs when the heat generated during high-temperature incineration is converted into high-temperature steam, which then activates a turbine, which powers a steam turbine generator, generating electricity. Furthermore, considering its equal calorific values to gas and petrol, the incineration of polyolefin plastic waste is a potential possibility for providing a substitute for traditional fuels. This technique converts medical waste into high-value items, contributing to a circular economy (Costiuc et al., 2015). However, it is important to recognize that medical waste incinerators may be environmentally beneficial if they produce a certain amount of energy for recovery activities. Nonetheless, incineration may become a source of pollution if flue gases are not well managed, creating pollutants such as sulfur oxides, chlorines, carbon monoxide, or dibenzodioxins (Teymourian et al., 2021; Thind et al., 2021). Notably, Geyer et al. (Geyer et al., 2017) predict that by 2050, more than half of the world's plastic rubbish will be burned. As a result, there is an urgent need for in-depth research and development of clean flue gas systems to effectively control emissions during waste combustion.

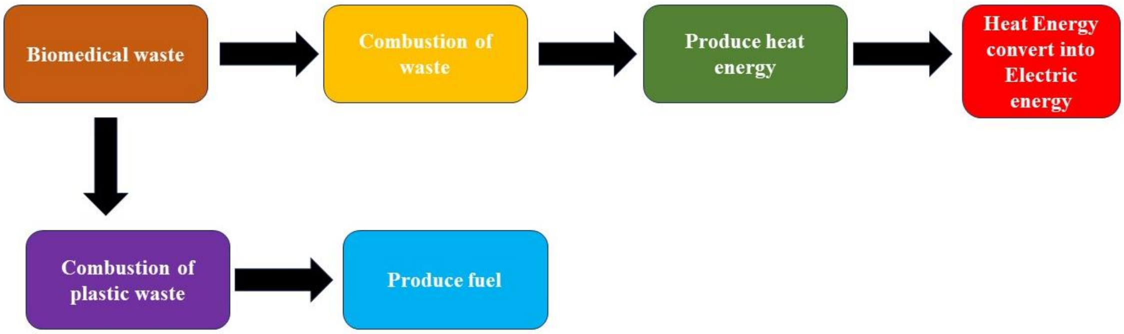

Figure 2: Brief mechanism of incineration for bio-medical waste management

Gasification:

Gasification is a thermal conversion technique used to treat medical waste, changing organic compounds into synthesis gases in a controlled oxygen atmosphere at high temperatures ranging from 800 to 1600°C (Awasthi et al., 2019; Zhang et al., 2021). The resultant syngas, predominantly comprised of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and chain compounds consisting only of hydrogen and carbon, may be recycled into feedstock or synthetic fuel (Teymourian et al., 2021). The choice between air and steam gasification greatly affects the creation of value-added products. Air gasification, generated by a ratio of oxygen and nitrogen, is reasonably uncomplicated, although it creates gases with a poor calorific value. In contrast, steam gasification utilizes steam as the medium, giving gases with high hydrogen values throughout the endothermic process but with a large energy requirement. The purified syngas, devoid of contaminants such as acid gases causing equipment corrosion and tar creating obstructions, may be effectively employed in gas boilers, internal combustion engines, or gas turbines to recover power (Sun et al., 2021).

Pyrolysis:

Pyrolysis is a thermal breakdown process used in medical waste to break down large polymeric molecules into smaller ones, either in the presence of limited oxygen or in an oxygen-free environment. Plastic waste, for example, may be thermally destroyed in the absence of oxygen at temperatures ranging from 540 – 830^o C (Wang et al., 2020). Pyrolysis may be classified as thermal or catalytic, with the former requiring an external energy source due to its endothermic nature and the latter requiring the use of a catalyst to accelerate chain breakages. Various feedstocks and operating conditions during pyrolysis result in end products of various states, including solids, liquids, and gases (Asim et al., 2021).

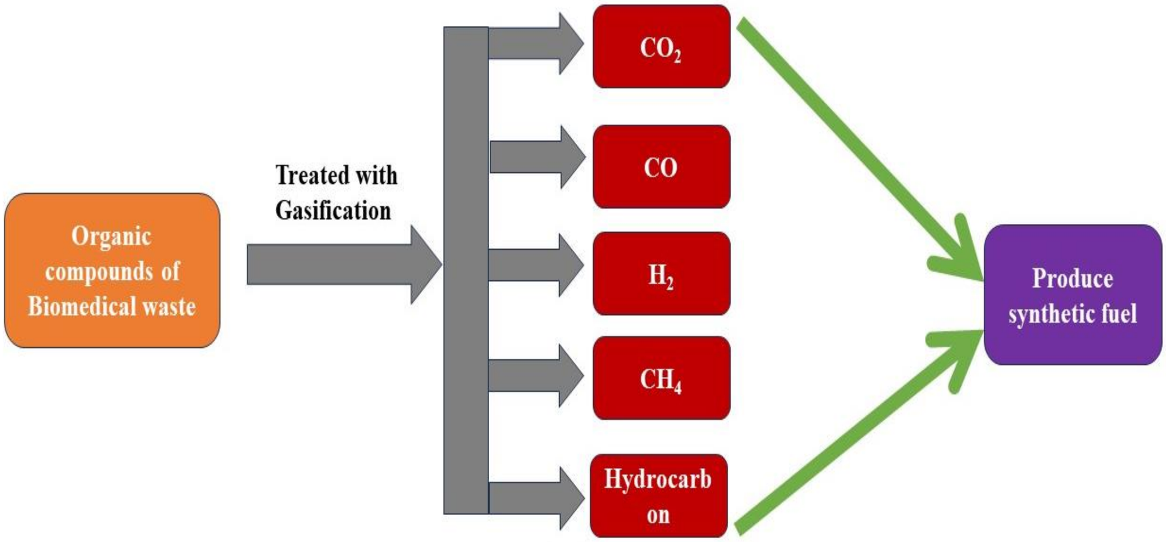

Figure 3: Through the application of gasification techniques, the organic compounds present in biomedical waste undergo conversion into syngas under elevated temperatures ranging from 800 to 1600^{0}C. These syngas can be utilized as a precursor for the production of synthetic fuels.

Plasma-Based Methods:

Plasma-based methods make use of the physical notion of plasma, which is the fourth state of matter and consists of radicals, charged ions, and free electrons (Shareefdeen et al., 2022). Depending on the energy sources and conditions during plasma generation, plasma technologies may be classified as hot or cold plasma. Thermal plasma is made up of electrons and heavier particles that are in thermal equilibrium, while cold plasma is made up of ions and neutrons that are at lower temperatures than electrons. In medical waste treatment, plasma-based methods such as plasma gasification, pyrolysis, and compaction are used as effective sterilizers. While plasma may produce valuable products such as syngas, hydrogen, and electricity, the enormous energy, density, and temperature involved with plasma treatment activities need caution. However, the technology has drawbacks, such as large capital costs and nitrogen oxide emissions (Erdogan et al., 2021; Munir et al., 2019).

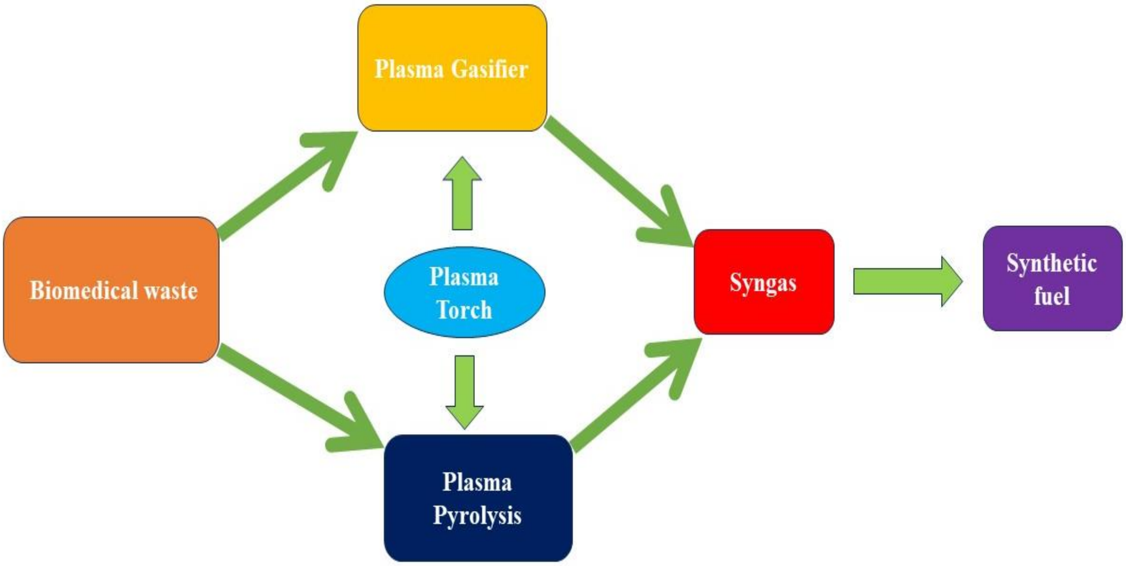

Figure 4: Biomedical waste can be effectively treated using either plasma gasification or plasma pyrolysis techniques. In both processes, the application of plasma enables the conversion of the waste materials into syngas, a valuable energy resource.

Carbonization:

Carbonization is a method of changing the carbon of polymer waste into homogenous carbonized goods, such as char or carbon-centric products incorporating carbon fibers and carbon nanostructures, by releasing volatile molecules (Asim et al., 2021). Carbonization may be categorized into dry and wet carbonization, with the former including torrefaction and the latter referred to as wet torrefaction. Dry carbonization, a simpler and more developed process, happens gradually under inert circumstances, whereas wet carbonization needs pressure and extreme temperatures (Zaini et al., 2017). Carbonization, particularly dry carbonization, is regarded as a possible option for medical waste transformation, but issues such as the creation of corrosive vapors from disposable face masks and the necessity for high-pressure reactors in wet carbonization must be solved (Joseph et al., 2021; Darmawan et al., 2017).

Hydrogenation:

Hydrogenation is a high-pressure process that degrades large hydrocarbon particles into small molecules by breaking C-C bonds in the presence of sufficient hydrogen and a catalyst. Through the reduction and saturation of organic components, this process converts plastic garbage into high-quality liquid fuels. However, the high cost of hydrogen, which is much more expensive than other fluidizing gases like nitrogen, as well as the need for hard equipment due to high pressure, make hydrogenation less prevalent than pyrolysis (Ragaert et al., 2017).

Liquefaction:

Liquefaction is a method of converting polymer waste into liquid value-added items like transportation fuel and chemical raw materials. This operation takes place at temperatures ranging from 300 to 450 °C and is pressurized with various solvents. In terms of hydrogen-

Table 1: Thermochemical Treatment Methods.

Thermochemical Treatment Methods	Description
Incineration	Mature technology for medical waste treatment. Minimizes waste volume at 90–95%. Requires flue gas cleaning system and integrated processes. Emits pollutants and needs strict emission control.
Gasification	The environmentally friendly method is more explored concerning coal treatment. Produces syngas for various applications. Requires further exploration in medical waste management. Needs stricter emission control compared to incineration.
Pyrolysis	High investment costs but profitable with an internal rate of return of up to 43%. Facilitates hydrogen production at high temperatures. Co-pyrolysis studies for enhanced oil production. Requires careful consideration due to the cost involved.
Dry Carbonization	Investigated for higher energy density products. Simpler process compared to wet carbonization. Value-added based on a relatively straightforward procedure. Continuous reaction limitation in wet carbonization.
Wet Carbonization	Moderate temperature, additional pressure. Suitable for wet medical waste. Continuous reaction limitation. Investigated for biochar and gas production.
Plasma-Based Methods	Utilizes plasma for waste management. High-energy, high-temperature processes for rapid heating and reactant transformation. Essential for achieving valorization of medical waste. Syngas, hydrogen, and electricity are valuable products. Requires careful consideration of energy costs.
Hydrogenation	Decomposes large hydrocarbon particles into small molecules with excess hydrogen and a catalyst. Transforms plastic waste into high-quality fuels. Higher transferring efficiencies of mass and heat. High-pressure requirements and expensive hydrogen stream compared to other gases.
Liquefaction	Turns polymers of waste into liquid value-added products. Processed at 300–450°C and pressurized with solvents. Applications include transportation fuel and chemical raw materials. Produces low-moisture, high-heating-value fuel. Needs further investigation for medical waste.

donating components and the depolymerization of plastic waste, liquefaction differs from thermal pyrolysis. Although liquefaction has advantages such as eliminating the requirement for feedstock drying and producing fuel with low moisture and oxygen concentrations, it still needs further research for medical waste applications (Ahmad et al., 2020).

Table 2: Thermochemical Treatment Operation Conditions.

Treatment Method	Temperature	Pressure	Reaction Agents	Oxygen Presence	Final Products
Incineration	High	Moderate	Oxygen	Oxygen required	Ash, flue gas, heat, electricity
Gasification	High	Additional	Oxygen/Steam	Varies	Syngas, ash
Pyrolysis	High	Moderate	Inert gas	Oxygen absent	Bio-oil, gas, char
Dry Carbonization	Moderate	Moderate	None	Oxygen absent	Char, gases
Wet Carbonization	Moderate	Additional	None	Oxygen absent	Biochar, gases
Plasma Methods	High	High	Plasma	Oxygen absent	Syngas, hydrogen, electricity
Hydrogenation	High	High	Hydrogen, Catalyst	Oxygen absent	High-quality fuels
Liquefaction	300–450°C	Pressurized	Solvents	Oxygen absent	Liquid value-added products

Biochemical Technologies:

Biological methods like biomethanation and fermentation, targeting biodegradable waste, convert organic compounds into valuable products. Biomethanation, or anaerobic digestion, produces methane-rich biogas and nutrient-rich digestate. Fermentation yields volatile fatty acids, alcohols, lactic acid, and hydrogen. These methods apply to wet agricultural and biogenic waste (Dudley et al., 2019).

Chemical Technologies:

Esterification, a chemical reaction between carboxylic acid and alcohol, creates esters and water. It is used for biodiesel and solvent production. Homogeneous and heterogeneous catalysts accelerate the reaction. For biodiesel, base-catalyzed transesterification is the preferred method (Khoshand et al., 2018).

Circular Economy & Biomedical Waste Management:

As of 2022, the country generates over 600 tons of biomedical waste daily, with an annual growth rate of 7-8%. Alarming statistics reveal that only about 20% of healthcare facilities comply with proper biomedical waste disposal regulations (Saxena et al., 2022). Currently, only a fraction of biomedical waste is treated through environmentally friendly methods, leading to severe environmental and public health concerns. By incorporating recycling and reusing strategies, the healthcare sector can substantially reduce its environmental footprint (Jacob et al., 2019). A circular economy is an economic system designed to maximize the sustainability of resources by reducing, reusing, recycling, and recovering materials and products. In contrast to the traditional linear economy, which follows a "take, make, dispose" model, a circular economy aims to minimize waste and keep products, materials, and resources in use for as long as possible. This approach promotes the continual use and regeneration of resources, contributing to environmental conservation and the reduction of negative impacts on ecosystems (Saha, 2023).

The integration of a circular economy is pivotal in addressing the challenges of biomedical waste management in India (Chew et al., 2023). Circular economy principles involve the reduction, reuse, and recycling of resources, minimizing waste and environmental impact. This approach aligns with Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), fostering sustainable practices. In the context of biomedical waste, embracing a circular economy model ensures efficient utilization of resources and minimizes the hazardous impact on public health and the environment (Mahjoob et al., 2023). Despite India's progress in biomedical waste management, the circular economy is not fully realized, with gaps in infrastructure and awareness. Establishing a comprehensive circular economy framework is imperative to enhance the sustainability and effectiveness of biomedical waste management practices in the country.

Conclusion & Future Directions:

The development of thermochemical treatments for effective waste-to-energy conversion is the future route of medical waste management. While various ways have been proposed, some of them, such as hydrogenation, liquefaction, fermentation, and esterification, are still in the early stages of research and are not well known. Because of the complexities of medical waste and the need for disinfection before recycling, chemical, and thermal treatments are currently seen as more suitable for energy recovery while also aiding in effective disinfection. Notably, heat disinfection has been shown to effectively sterilize contaminated materials, including viruses such as COVID-19, in laboratory tests (Kaur et al., 2023). Incineration, gasification, pyrolysis, and carbonization are currently more feasible and economically viable thermochemical processes for medical waste-to-energy. While carbonization requires the least amount of heat, incineration, gasification, and pyrolysis need higher temperatures, resulting in varying degrees of medical waste degradation. The oxygen requirements and types of solid waste produced by incineration and gasification, in particular, differ. It is critical to understand the strengths, weaknesses, opportunities, and threats (SWOT analysis) of incineration, gasification, pyrolysis, and dry and wet carbonization before making informed decisions. Incineration is an established technique that may reduce waste volume, but it requires additional equipment for flue gas purification and integrated operations. Gasification, which is more environmentally friendly than incineration, needs further research. Despite high initial expenses, pyrolysis has the potential to be profitable, with an internal rate of return of up to 43%. Due to the limitations of continuous reactions in wet carbonization, dry carbonization should be investigated further for products with higher energy density products. Collaboration between politics and technology is essential, especially in light of increased medical waste. To promote proper waste disposal methods, clearer and stricter norms and regulations are essential, particularly in developing countries. Governments are being pushed to build a comprehensive infrastructure for waste collection, sorting, transportation, and valuing. The selection of waste-to-energy technologies should be based on the amount of medical waste, with mature technologies such as incineration suitable for regions with high waste volumes and environmentally friendly technologies such as pyrolysis and gasification encouraged in regions with low waste volumes. Sorting waste at the source, establishing handling capacities, and enforcing emission limitations via law all contribute to effective medical waste management and energy recovery.

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