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Latest insights on technologies for the treatment of solid medical waste: A review

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ABSTRACT

Nowadays there is a growing concern in the treatment of solid medical waste due to the increase in waste generation that has been accelerated by the pandemic. This accentuated the problems of medical waste management, related to separation, storage, and transportation. In addition, current medical waste treatments are not globally accepted, since most of them generate pollutants, or simply not all treatment technologies are applied correctly. This review analyzes the basis for proper management, and the main existing technologies and developments carried out so far. An exhaustive comparison between them allows for distinguishing the pros, cons, scales, and applicability of each one. This is complemented with a TRL analysis to describe their degree of development. Furthermore, some waste-to-energy (WtE) alternatives are discussed since they represent an appealing option that can positively affect the environment and the economy of existing technologies. Finally, some tools and technology selection criteria shown in the literature are presented, along with some discussion of their economics. This paper exposes a theoretical approach based on the literature on the current situation of solid medical waste treatment and provides the basis for decision-making to implement some existing technologies. Likewise, it presents the limitations in the current system that are the kick for future research.

1. Introduction

Medical waste (MW) is composed of a wide range of materials, for example, utilized needles and syringes, body parts, drugs, diagnostic samples, blood, synthetic substances, medical devices, radioactive materials, and surgical masks. It can be considered as a subgroup of all wastes generated at healthcare facilities. Typically, hospital waste could be hazardous or non-hazardous. Exposure to hazardous waste induces physical, chemical, or microbiological hazards to the population and medical care laborers related to handling, treatment, and removal of waste [1]. It is estimated that around 15 % of the total MW is assumed to be hazardous MW [2] and this value could reach as high as 35 %, depending on the characteristics of the waste and the remaining is nonhazardous. Hazardous waste is divided into infectious and non-infectious or dangerous waste. Infectious waste contains pathogens that could provoke an infectious disease in a susceptible host; thus, it requires special treatment to inactivate the corresponding biohazards [1]. On the other hand, dangerous waste could produce poisoning, intoxication, reproductive health problems, or physical injuries. Nonhazardous or general waste can be processed through regular procedures and does not require any special handling (Fig. 1).

The healthcare industry is viewed as the fifth-biggest producer of greenhouse gases (GHGs) around the world, comparable to 4.4% of global net emissions, and the second biggest contributor to landfills after the food industry [3]. Medical waste generation is growing quickly at a yearly rate of around 20% [4]. This rising amount of medical waste is due to the increase in the elderly population, the improvement of health awareness and with it, the better quality of life, the rise in medical services expenditure, the use of non-returnable packaging, and the development of medical technology, and consequently, the growth of healthcare industries. However, the SARS-CoV-2 (COVID-19) pandemic has accelerated the environmental pollution and public health crisis dramatically (Fig. 2A) [5]. Since solid MW is mainly composed of plastic materials, there was a high increase in plastic generation with it [6], [7]. It was estimated that medical waste generation from the pandemic increased significantly by around 18–425 % depending on the country, representing an increase from 200 t/d to over 29,000 t/d by September 2020 around the world [8]. Overall, 2.9 million tons of MW has been generated in the first 8 months of the pandemic. The demand for personal protective equipment (PPE) is estimated to increase by 20 % by

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2025 [8]. Then, healthcare waste (HCW) might not get recycled or safely disposed of due to the huge amount generated in the last period, rushing the need for proper management.

This growing trend is reflected by an increased number of papers published in the last few years about MW. According to [9], countries with transient economies have released many papers, in comparison with rich countries. Affluent countries also have a larger rate of med-waste generation, while low-income countries have a lower rate (Fig. 2B). It is linked to the technological development and economic power of a country. Rich countries have higher Economic Performance Index (EPI) scores, indicating that they have better controlled solid waste management despite having the highest generation. But their higher production is due to higher Human Development Index (HDI), Life Expectancy (LE), and Healthcare Expenditure (HE) scores [10]. Developing countries generate less waste than developed countries, but they face serious problems with human health and environmental pollution because they do not have regulated waste collection and disposal systems [11]. It was confirmed by [10] who reported a study made in 24 low-income countries in which just 58 % of the facilities had adequate disposal of healthcare waste. Actually, open dumping of contaminated sharps with infectious diseases and respiratory difficulties has been reported in numerous countries with economies in transition [12].

Public health consequences of the COVID-19 pandemic put in evidence the precarious recycling and management of MW, particularly in developing countries. Inadequate management of MW can provoke severe public health consequences such as injuries and infections, but also cause damages to the environment which impact indirectly the human health [13]. It can transmit hepatitis B and C, HIV, and other blood-borne diseases [11]. Such diseases cause 0.4–1 million deaths each year. For this reason, a special commitment to decreasing health difficulties and environmental contamination ought to be applied.

The composition of MW is intricate and dependent on factors like season, hospital patterns, and location. MW may contain either inorganic or organic material, leading to a calorific value that can range from 2 to 40 MJ/kg [14]. However, MW is mainly constituted of various

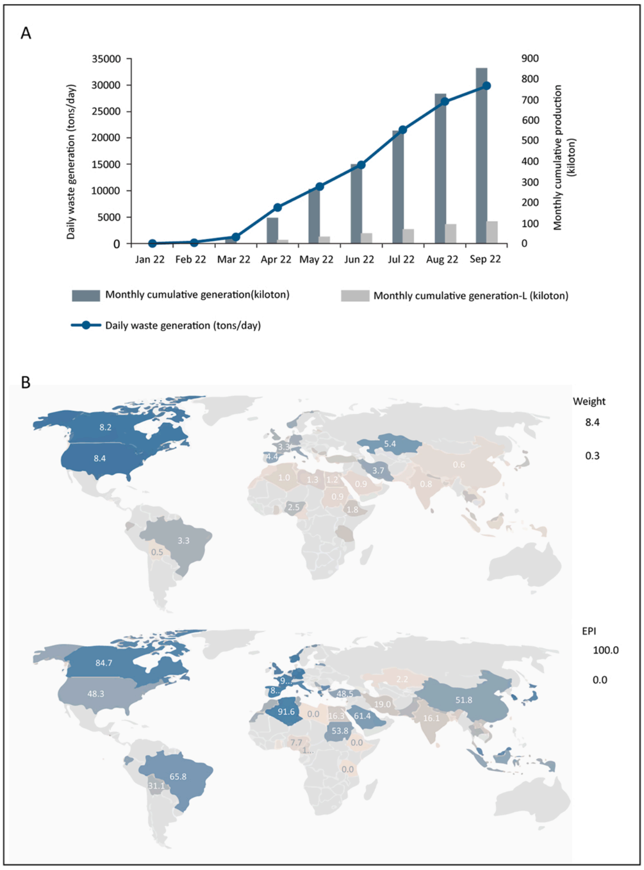

Fig. 2. (A) Medical waste generation around the world on different dates [5]. (B) Medical waste generation in different countries and their environmental performance index (EPI) of controlled solid waste management Adapted from [10].

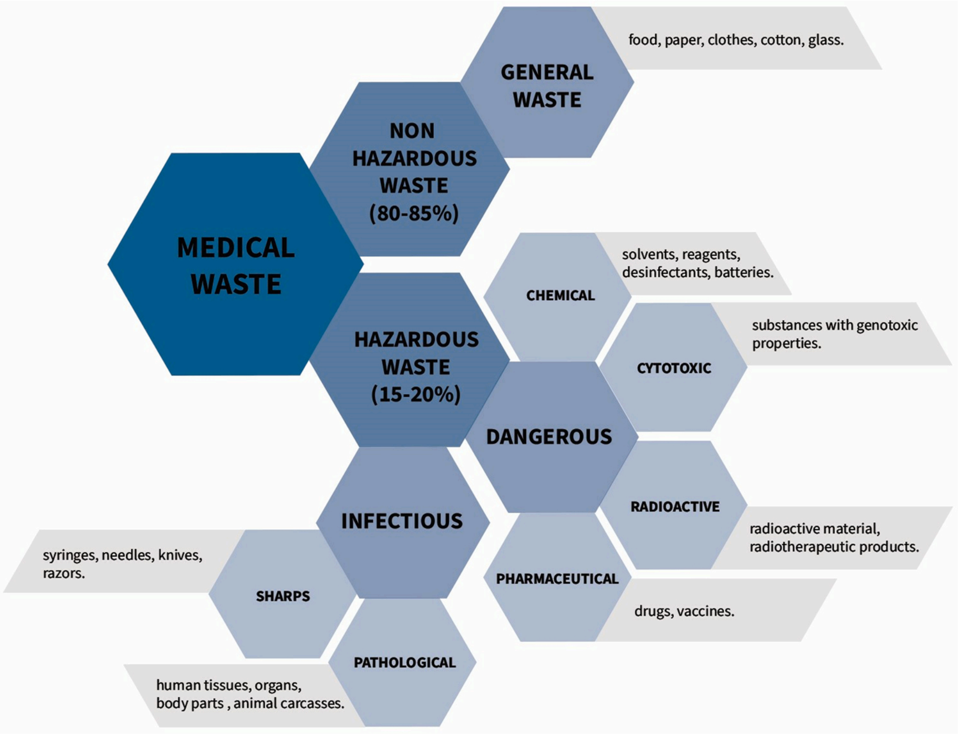

Fig. 1. Medical waste classification.

types of plastic materials, representing approximately 35 % of them [10]. Plastics have a high hydrogen and carbon content, while the quantity of oxygen is lower than many other feedstocks; and nitrogen and sulfur contents are approximately close to zero [15]. For this reason, MW is an excellent raw material that possesses high heating value to produce valuable products. However, if they are treated inappropriately like using incineration alone, they can contribute to the emissions of CO_2 and GHGs to the environment.

Efficient waste management drives a positive impact on the economy, which would be reflected in the reduction of costs for waste disposal, and in the generation of employment, added to the advantages from the point of view of human health and the environment. However, all the traditional technologies have shortcomings, such as the time required, byproducts produced, energy consumption, and cost framework, which rushes the need for technological advancement to overcome these limitations. Technological advances are not only required to treat MW but also there is a necessity to make management more efficient throughout its chain. Alternatively, waste converted into energy with clean technologies instead of using incinerators means a new approach to thermal technologies.

The objective of this paper is to present the progress in the field of solid medical waste treatment, to give rise to new advances, and to be able to make decisions for the selection and implementation of an adequate MW management system. This paper begins by laying out the foundations for proper management, and some methods used for segregation, identification, and transportation of MW in order to reduce as much as possible any risk they generate. Then, the existing technologies for the treatment of MW are briefly described, and due to the energy potential that some of them have, the concept of Waste-to-Energy (WtE) is introduced. Some cases of energy generation are commented on. Finally, based on the information present in the literature, a technical and economic analysis was developed. An exhaustive comparison of all the mentioned technologies was carried out, and a TRL (Technology Readiness Level) analysis was implemented to determine their degree of maturity and development. In addition, the different tools used by several previous investigations to select the most appropriate technologies were analyzed. This serves to categorize the technologies from the technical, social, and environmental points of view, for future decision-making.

2. Management of medical waste

The existing MW management system needs to be more standardized. It is necessary to establish a regulatory system capable of managing waste identification, collection, classification, storage, transportation, treatment, and removal with a cradle-to-grave perspective (Fig. 3). However, management of MW is not only a legal duty but also a social responsibility in which training or health education can help to increase awareness and reduce accidents and environmental pollution [16].

Segregation of waste at source is a key step, especially to decide its destination, whether to recycle, reuse or undergo further treatments. The classification is made according to the composition, or disposal method used in the waste flow. Nonhazardous MW is separated and disposed of as municipal waste, because it does not pose a risk to health and the environment, while hazardous MW must be undergone special treatment. Segregation reduces transportation costs, diminishes the volume of the waste stream, minimizes the contamination of MW that can cause health problems and environmental pollution, and prevents contamination of MW from non-medical waste guaranteeing that only infectious materials are discarded in the infectious waste stream [17]. In the context of MW valorization, source separation is also recommended to avoid any waste that has no net energy content and does not produce electricity, thereby reducing overall efficiency [18].

Packaging, like plastic bags, cardboard boxes, and containers, must be made in such a way that its aspect (color, shape, size) allows the classification of hazardous MW at the place of origin [19]. Once packed, tracking is essential to assure the bin reaches its destination. Intensive use of bar codes, QR codes, radio frequency identification (RFID), and

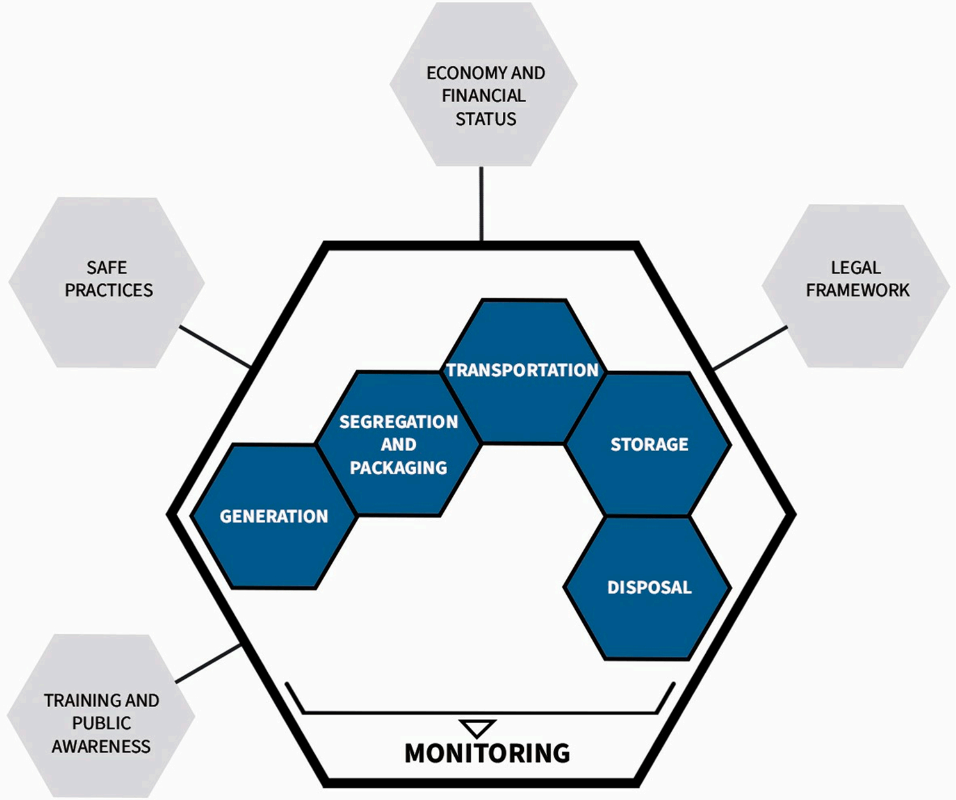

Fig. 3. Structure of the MW management.

micro-sensors are the base of many identification systems [20]. In addition, some authors developed novel models and strategies to overcome these issues. [21] provided an innovative and successful deep-learning approach for the automatic detection and classification of MW. [22] proposed a tracking system of the container from the collection to dump disposal to control traceability and avoid hazards caused by the mismanagement of waste. [23] designed an MW supervision model based on the blockchain along the entire process, that is generation, transportation, treatment, and destruction of MW, and allows for the detection of MW irregularities.

MW produced in healthcare facilities is moved to a pre-decided area within the healthcare facility before disposal. The place should be a closed room, sufficiently extensive to receive the maximum amount of waste of different categories that must be stored independently, and should be suitable for refrigerated storage of the waste in cold rooms [11]. There, MW should be stored based on the type, group, and characteristics of hazardous waste in containers. Such containers should be strong, rust-resistant, not easily opened, watertight, and have a lid [24]. It is advisable the use of labels and symbols of hazardous materials to prevent work danger. Then, the stored MW should be transported to the site of disposal and the weight of the MW should be verified after arrival in the disposal facility to avoid losses.

Finally, the transport of MW should assure closeness, and reduction of time and costs. In general, transportation cost is uncommonly high because of the wide distribution of every clinical facility [6]. It is important to design an optimal logistics process for successful management. Routing models are being designed to assure an optimized system of distribution, like [25] which presented a mathematical programming model based on reverse logistics with a bi-objective approach to solving the location-routing problem and thus minimizing total transport cost and population risk. An interesting approach is given by [26], which introduced a multi-objective model to build an MW reverse logistic network through mobile processing centers. In this way, a rapid response giving a better distribution of capacity according to the treatment centers' availability, in a cost-efficient way, is presented to overcome emergency cases such as COVID-19.

3. Pretreatments

Pretreatments mainly consist of mechanical processes such as shredding, grinding, mixing, liquid-solid separation, agitation, pelletization, and crushing. It has the benefit of decreasing the total volume of the waste but does not eliminate infectious pathogens or disinfect equipment. It facilitates further chemical or heat treatment by increasing the specific surface area of the solid pieces [27]. Shredding is the most common process used either as pretreatment or post-treatment. It reduces the volume by up to 80 % with a single or multiple-shaft shredder specially designed. The advanced shredders are ordinarily low-speed, high-torque, single-pass shredders with easily replaceable cutters and with release screens to control the size of shredder waste [28]. Pelletization is another of the treatments employed to modify the characteristics of the waste. It compacts MW into regular particles with pellet or briquette shapes. This makes raises its density, lowers the moisture content, increases the calorific value, homogenizes physical and chemical properties, and facilitates storage. It also simplifies handling and transportation. Pelletization is also used as a post-treatment after thermal operations for further processes [29]. In general, pretreatments depend on the further process in which the waste will be submitted, adding agitators, filters, or paddles as appropriate.

4. Treatments

4.1. Steam sterilization

Steam sterilization by autoclaving is the second most used treatment after incineration [30]. It sterilizes all infectious waste, both laboratory waste and medical waste [31]. It is a low-temperature treatment technology that involves a synergy of increased temperature, pressure, and time to deactivate the microorganisms. Autoclaves heat the waste to temperatures high enough to disinfect but not sufficiently hot to burn and create air pollutants. Treatment of pharmaceuticals, radioactive and pathological waste is not suitable with this method. Furthermore, it does not apply to huge quantities of hazardous waste [32]. Due to these limits, it needs strict classification. Once the waste is treated, it is disposed of in a sanitary landfill as non-infectious waste.

The autoclave consists of a cylindrical metal chamber surrounded by a steam jacket, whose construction materials should be resistant to pressures and temperatures to operate safely (Fig. 4A) [33]. MW is loaded to the closed pressure sterilizer and steam is injected into the system to keep a specific temperature for a given time. The steam jacket reduces condensation in the vessel and diminishes the loss of heat. Thus, MW is heated by the latent heat liberated from high-pressure steam, which causes protein denaturation of pathogenic microorganisms. Not only MW is treated, but also waste liquid and waste gas can be decontaminated [34]. Several types of autoclaves are available, such as gravity-fed, pulse, or multi-vacuum cycle autoclaves [35]. In addition, the solar autoclave was proposed as a renewable source of energy to destroy microorganisms [36]. There are also hybrid or integrated autoclaving technologies, which are considered advanced methods. These alternatives employ steam treatment with vacuuming, internal mixing, fragmentation, drying, and compaction increasing the capital costs compared to standard autoclaves. These systems are being used to improve heat transfer to waste, altering the physical appearance of medical waste and making this technology a continuous process. On the other hand, a hydroclave is a variety of autoclaves. It is a double-walled tank where steam is infused in the external jacket to warm the interior of the machine, but it is never in touch with the waste. Heating induces the dissipation of the moisture contained in the waste, increasing the pressure [37]. However, it requires more steam to heat up initially in comparison with the autoclave [33]. Similarly, a chemiclave is used to sterilize surgical instruments incorporating steam, alcohol, and formaldehyde under pressure. In this sense, it uses an unsaturated chemical vapor instead of steam to generate a killing vapor [38].

Sterilization efficiency depends on many variables such as internal temperature, the strength of steam penetration, quantity of residual air, duration, sterilization pressure, composition, density, liquid content, weight, and types of containers [39]. During the process, physical, chemical, and biological monitoring are needed to guarantee the efficacy of the treatment. Physical monitoring is performed during each sterilization using thermometers and manometers built into the autoclave. Chemical monitoring allows insight into the material that has been exposed to a certain temperature for a certain period. Biological indicators are the most important to ensure the efficacy of sterilization and are the only method of checking its success [33].

This method requires significant energy and produces toxic gases and liquids liberating odors that require additional purification treatment technology to avoid releasing pathogenic compounds into the atmosphere. In addition, it does not significantly reduce the volume of waste to be landfilled [40]. For that, MW should be shredded before or after sterilization. Despite producing emissions, they are not significant as occur with other methods. Volatile emissions usually occur when the treated waste is not segregated in the source, resulting in significant content of toxic compounds. Moreover, it does not produce strong carcinogenic dioxins and does not generate toxic waste due to operating conditions [34]. It is well-established, reliable, efficient, and simple to operate, has low installation and maintenance costs, the rate of processing speed is quick, and allows good sterilization thanks to the strong penetration [15].

4.2. Microwaving

Microwaving is a sterilization process based on the principle of

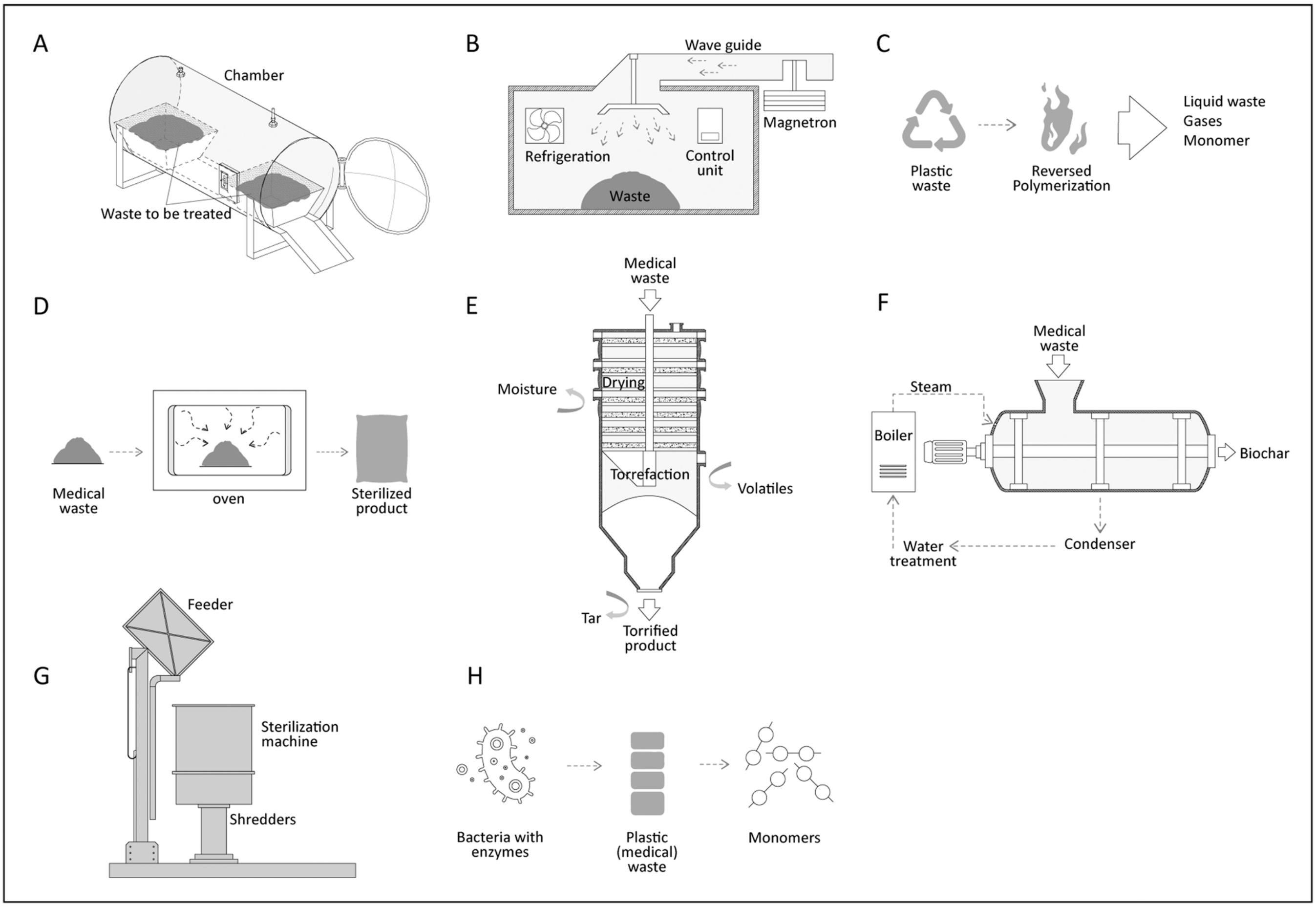

Fig. 4. Diagrams and schemes of low and medium thermal technologies. (A) Autoclave. (B) Microwave oven. (C) Depolymerization. (D) Dry heat treatment. (E) Torrefaction treatment. (F) Hydrothermal carbonization [56] (G) Converter machine [20]. (H) Biological treatment.

generating high-frequency short waves that cause the vibration of particles, emitting heat up to 200 °C (Fig. 4B). The system cannot reach higher temperatures due to the inert environment created by nitrogen [41]. Therefore, it generates energy by moist heat and steam due to the thermal effect of an electromagnetic radiation spectrum. The heat generated due to the oscillation of the liquid molecules kills all pathogens and reduces the likelihood of infection [42]. An important parameter is humidity because this method is only effective when the waste is damp. For that, a humidifier is usually incorporated into the microwave units [27]. Higher water content favors the effectiveness of the sterilization process, as occurs at higher microwave power and sterilization times [43]. A previous shredding can be installed to enhance the efficacy of the treatment. This process should not be used for cytotoxic, volatile compounds, body parts, large metal items, and dangerous chemical or pharmaceutical waste [44]. In particular, metal content creates reflection surfaces giving rise to a non-uniform treatment. Thus, they should be subjected to special treatment [45]. On the contrary, it is suitable for processing infectious waste and pathological waste.

Microwave units can be batch or semi-continuous [12] and can be used for on-site or mobile treatment. Medium scale device using an internal shredder is the most common microwave device reported. Instead, small batch units are also available and can be used in small hospitals, clinics, or departments of a large hospital. This technology has the advantages of selective heating, shorter heating time, and no direct contact with materials as compared to conventional thermal treatments [46]. In addition, it has high efficiency, low pollution, and limited heat loss [41]. It is completely closed, fully automated, and easy to operate. After treatment, MW can be disposed of in a sanitary landfill as domestic waste and the wastewater produced should be treated, discharged, or reused [42]. On the other hand, the cost represents the main drawback; it involves huge capital investment and high running costs which make this process not economically competitive with the other technologies hampering its large-scale deployment in developing countries [12].

4.3. *Reverse polymerization*

Reverse polymerization (RP) is the reduction of organic material through the use of microwave energy in an oxygen-depleted or nitrogen-rich environment (Fig. 4C). This technology decomposes complex molecules into simpler chemical compounds. During this process, combustion does not take place, reactions occur at moderate temperatures and the control of the process is more precise since the energy input is variable [35], [47]. The hindrances of the technique include the utilization of a scrubber to control gaseous emissions, and the production of wastewater, which should be treated. The cost is one of the greatest and may adversely influence public acceptance [48].

4.4. *Dry heat treatment*

Hot air ovens could be used to sterilize infectious MW (Fig. 4D). Conduction, natural or forced convection, and thermal radiation at higher temperatures and longer exposure times than steam-based processes are applied in order to meet minimum disinfection levels [28], [49]. This technology destroys microorganisms by oxidizing molecules. It is easy to install, has relatively low operating costs, is not corrosive for metal and sharp instruments, is non-toxic for the environment and the heat penetrates materials. However, it has a slow rate of heat penetration and is not suitable for most materials like plastics.

4.5. Carbonization

Carbonization is a thermal treatment in which organic waste like plastics is converted into solid carbon materials [50]. A variety of products can be obtained with this method, like hydrochar, activated carbon, carbon nanotube, graphene, carbon fibers, and carbon spheres [51]. In general, it is categorized as dry and wet carbonization.

4.5.1. Dry carbonization

It is a thermochemical process carried out in an inert atmosphere in the absence of oxygen under ambient pressure and temperature of 200–300 °C with low heating rates [52]. It is also called torrefaction or dry torrefaction (Fig. 4E). First, the evaporation of moisture takes place at a temperature of about 100 °C, leading to large mass loss. Then, the volatile matter is released, and char is produced. The volatile matter liberated can be captured and condensed at low temperatures, producing an oily liquid product.

Char is a homogeneous carbonized product with high carbon content and low oxygen, giving rise to elevated energy density and decreased self-ignition point [53]. As a result, it becomes easier to transport and manage. Additionally, it gives a product easy to granulate, hydrophobic, and stable for long time storage. Torrefaction is a simple and well-establish operation, which can be implemented either on a small or large scale. Moreover, this process requires raw material with low moisture content but being MW fundamentally dry, it tends to be torrefied directly without previous treatment [54].

4.5.2. Wet carbonization

Hydrothermal carbonization (HTC) is a thermochemical conversion of polymer-derived or organic waste into value-added coal called hydrochar (Fig. 4F). It is generated by a series of reactions which include hydrolysis, dehydration, de-carboxylation, and finally aromatization, condensation, and polymerization. This product has a heating value that varies from 2.72 MJ/kg to 38.3 MJ/kg depending on the operating conditions. It can be used as fuel, catalyst, carbon sequestration, and adsorbent [51]. Along with the hydrochar, liquid fractions and a small number of gases are also formed. According to the operating conditions, HTC can be classified as hydrolysis (80–180 °C), hydrothermal carbonization (280–300 °C), liquefaction (280–370 °C), hydrothermal catalytic gasification (<550 °C, pressure less than 22 MPa) or supercritical gasification (370–700 °C, pressure higher than 22 MPa) [55]. HTC is broadly applied with biomass feedstock, however, [56] studied the effect of hydrothermal carbonization mixing MW and wood chip successfully.

This process is suitable for materials with high moisture content. As MW is generally dry, it needs the addition of water to undergo this treatment. The water acts as solvent and reaction medium, accelerating the reaction and improving the overall efficiency [51]. However, it requires high-pressure reactors. Consequently, energy for pressurization and heating is considered high and faces difficulties for continuous processes.

4.6. Converter technology

Converter technology is an innovative process in which several different operations such as pasteurization, sterilization, grinding and pulverization, trash compaction, dehydration, and cooling are compacted in the same unit. The period of one cycle is about 30 min and significant reductions in weight and volume are achieved [57]. This technology encompasses the entire process to treat MW, so there is no intermediate handling of the waste within the process.

A converter could be operated under atmospheric pressure. Nonetheless, superheating conditions and steam generation can be accomplished by variable pressure control, which is a consequence of cycling between ambient and negative pressures inside the treatment chamber. Rather than utilizing external water input, converters use the dampness present in the treatment chamber to acquire steam disinfection. It is a clean and chemical-free technology, reliable in terms of usability and maintenance, and does not discharge any unsafe emissions or radiations [1]. Shredding is carried out via sharp cutting blades, for which the volume is decreased. The converter can be installed in hospitals for on-site treatments due to its compact size, which also reduces the transportation costs of MW.

A variation of this machine was implemented in Texas, called Med-Shred Inc [57]. The system consists of a mobile shredding and chemical disinfecting machine, which was used to transform toxic MW into disposable municipal waste helping to reach better management of waste in hospitals. Converters are also applied in middle eastern countries [1]. Among them, a converter machine was reported in Turkey which produces a product with high heat content, generating an output of about 25 MJ/kg [58]. It was also designed a similar prototype in Italy, designated to treat local medical waste (Fig. 4G). The project is intended to produce a fluff for further energy valorization [20].

4.7. Bio converter

This technology employs a solution of enzymes to disinfect MW (Fig. 4H). The final product is a sludge whose water is removed for sewage disposal and the solid waste is sent to the sanitary landfill. Not an excessive number of technologies that work on biological procedures are accessible on the market because it is still in the research and development stage. However, this system has been tested in the USA and is mostly used in agriculture animal waste due to its capacity for large applications (10 t/d). The incorporation of biodegradable plastics can help to treat MW. Microbes use biodegradable polymers as substrates under starvation and produce enzymes that can degrade biologically biomedical implants built with biodegradable plastics. Further research needs to be developed for large-scale manufacturing of biodegradable plastics and the corresponding biological treatment [59], [60].

4.8. Incineration

Incineration is the most used thermal treatment for the disposal of MW. It is a high-temperature process, which varies from 980° to 2,000 °C (Fig. 5A). It involves the burning of organic materials in the presence of excess oxygen to ensure complete combustion. The main advantage is the significant reduction of the volume of material, diminishing it up to 90 % [35]. The main products of combustion are ash, flue gases, particulates, and heat. It is a stable activity and provides great disinfection, sterilization, and pollutant elimination. Well-designed incinerators can regulate combustion air and control feeding rates, and they also employ sufficient residence time to destroy all MW [1]. One of the main advantages is the broad applicability, but despite this technology is suitable for all kinds of infectious MW, it is not advisable for pressurized gas containers, reactive chemical waste, silver salts, PVC plastics, heavy metals, batteries, sealed ampoules or vials, radioactive materials, and unstable pharmaceuticals [61].

Toxic and carcinogenic compounds may be emitted during the process, such as polychlorinated dioxins and furans. In particular, dioxin content is especially high in textiles, medical supplies, and plastic products [62]. Incineration also promotes the production of bottom slag and fly ash as hazardous by-products which have a high concentration of toxic metal; and produces other harmful gases, such as hydrogen chloride, hydrogen fluoride, and sulfur dioxide, which require an exhaust gas purification system [40]. Regarding dioxins, their formation is related to the composition of waste, combustion conditions, residence time, the chlorine content in flue gas, heavy metals, and remaining carbon in fly ash. Since plastic materials are the main constituent of MW, the presence of chlorine from plastics represents the main cause of high dioxins emissions from waste incinerators. However, those emissions are

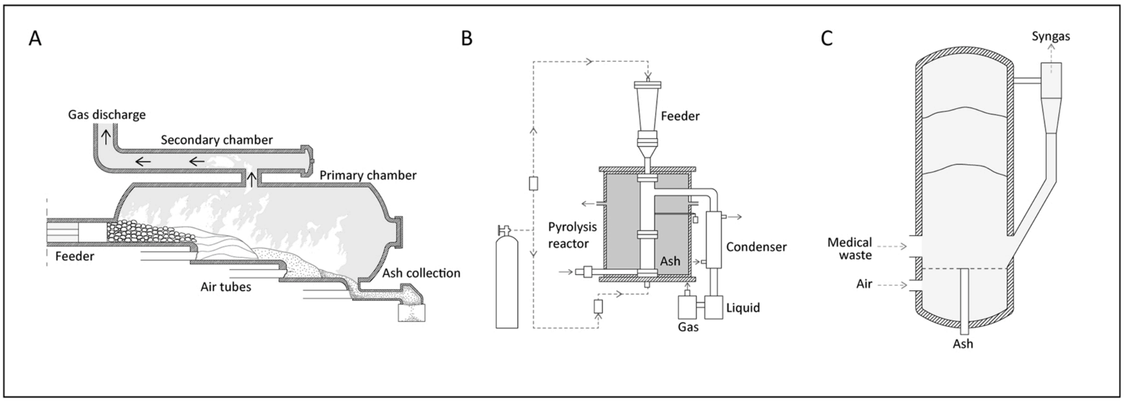

Fig. 5. Diagrams and schemes of high thermal technologies. (A) Common air incinerator. (B) Pyrolysis equipment. (C) Fluidized bed gasifier.

mainly released due to poor combustion control. For that, med-waste incinerators require special monitoring of emissions to assuring the good quality of the air and the environment. If they are not well-controlled, they can cause damage to the health, and the environment, and produces technical problems, such as corrosion of tubes [63]. As a consequence, special training on the procedures are also needed for using incinerators.

Factors that influence the level of removal of MW in the combustion process are temperature, the water content in waste, the shape of the combustion chamber, characteristics and types of MW, time, and turbulence [24]. The incinerator is also required to have a high and stable temperature, good oxygen mixing conditions, and sufficient gas residence time to ensure proper treatment.

Some incinerator configurations are rotary kiln incineration, fixed bed furnace incineration, and pyrolysis incineration. The rotary kiln incinerator is the most extended technology used due to its adaptability and reliability through incineration [62]. Despite incineration being generally used for large-scale applications and off-site treatment, smaller devices built with nearby materials are at present being tested and implemented in various nations [64]. Similarly, portable incinerators are increasing attention in developing countries as they permit on-site waste treatment in hospitals and clinics, thus avoiding the need to transport infectious waste across the city [10].

4.8.1. *Post-treatment of ashes and gasses*

The effectiveness of an incineration process is dependent on the capability of managing the emission pollutants. After incineration, pollutants are vented directly into the atmosphere or are emitted going through treatment in the air pollution control (APC) unit. The remaining heavy products are concentrated in the bottom and fly ash residues present as trace elements, whose chemical composition depends on the characteristics of the waste incinerated [65].

Fly ash is the unburned residue from the process of incineration, which rests in the boiler filter. Treatment of fly ashes has been broadly studied, and many methods have been proposed, such as vitrification through plasma technologies, mechanochemical degradation, hydrothermal degradation, photocatalytic treatment, biodegradation, cement solidification, flotation, microwaving, supercritical water oxidation, catalytic hydro-dichlorination, roasting, melting technique, water washing pretreatment, and acid leaching pretreatment. [66], [67]. The ash produced is comprised of dioxins, heavy metals, chlorides, and carbon constituents. In consequence, it is designed as hazardous waste [18].

On the other hand, bottom ash contains fewer amounts of heavy metals and is considered safer [68]. It is collected from the base of the furnace and represents the major portion of the solid residuals. Fly ash and bottom ash produced from MW are enriched with heavy metals [65]. These metals cause pollution and require further treatment. Cement solidification, chemical stabilization, self-propagating high-temperature synthesis, furnace melting, or mixes of them are some of the techniques used to eliminate heavy metals. Additionally, ethylenediaminetetraacetic acid (EDTA), supercritical water treatment, and phosphoric acid stabilization can reduce their concentration to below the allowable limit [69]. These methods demonstrated to be efficient, so the ash after treatment can be disposed of as non-hazardous waste.

Finally, gasses produced during incineration should be treated before being liberated into the atmosphere. Post-treatment of gasses could be controlled by an APC device, which consists of a series of techniques employed to reduce or eliminate the emission of hazardous compounds. They can be condensers, gas quenchers, water, or alkali scrubber, catalytic converters, carbon filters, sprayers, bag filters, id fans, and chimneys [24].

4.9. *Pyrolysis*

Pyrolysis is an endothermic process that degrades MW in the complete absence of air (Fig. 5B). The main products are char, pyrolysis oil, and syngas and the proportion between them may change depending on the feedstock and conditions utilized. It is usually called thermal pyrolysis or catalytic pyrolysis when it employs a catalyst. Catalysts are utilized for overcoming the issues of the inferior quality of liquid oil, impure fuel gas, and high energy consumption [53]. This treatment can be also grouped into slow (270–630 °C), quick (580–980 °C), and flash (780–1030 °C) pyrolysis in light of the heating rate [70]. The selection of the process should be adjusted according to the final product. In general, slow pyrolysis is chosen to maximize the solid product yield, whereas fast and flash pyrolysis benefits the yield of liquid products. The characteristics of the products obtained by pyrolysis using MW are encouraging, obtaining a high calorific power, especially for liquid products [71]. In this sense, [72] studied the optimal parameters for the production of liquid products from plastic MW, while [73] examined the reaction mechanisms and pyrolytic behavior of two specific types of MW: syringes and medical bottles.

The main objective is the conversion of feedstock into a condensed liquid composed of a complex combination of more than 300 compounds. The properties of the liquid products are very near commercial transportation fuels and can accordingly be utilized as an alternative fuel after upgrading [74]. It is necessary to work under optimized conditions for the production of bio-oil, so very little biogas could be generated, which is normally released into the air or reused in the pyrolysis process. The remaining biochar produced could be used in many applications such as a catalyst, adsorbent, anode material, and photocatalytic support [75].

Pre-treatment is recommended, especially drying and grinding, to carry on pyrolysis. The humidity and size of the waste have a direct influence on the performance of the treatment. Little particle size is valuable to further improve the reaction efficiency, decrease the yield of PAHs, and elevate the production of biofuels. Pyrolysis is suitable for all types of MW, but due to operation, maintenance requirements, and pretreatments, it consumes a high quantity of energy making the process expensive [15]. In addition, it is not easy to achieve stable combustion, producing noxious gases such as PAHs, HCl, SO_2, and NO_x which represents a threat to public health and ecological security [31].

4.10. Gasification

Gasification is an endothermic conversion process that mostly produces syngas by heating the feedstock at high temperatures between 600 and 950 °C within conditions of oxygen deficiency (Fig. 5C). Gasification consists of four major zones: drying, pyrolysis, tar cracking, combustion, and reduction. Drying occurs at a low temperature of about 100–200 °C and the moisture content is highly reduced. The pyrolysis phase is characterized to produce tar and gaseous fractions; further combustion provokes the decomposition of these products generating a gaseous mixture of smaller molecules; and finally, gasification which produces the final syngas [76].

This technology can provide multiple products such as heat, gaseous and residual amounts of sub-products like ash and impurities including dust, alkali compounds, nitrogen, sulfur, chlorine, fluorine, and tar. Tar and dust are the main factors limiting the application of syngas. Among them, tar is a viscous liquid composed of a complex mixture of condensable hydrocarbons with a high molecular weight. If it is not well-managed can cause blockages in pipelines, producing serious damage to the equipment under operation. For that, it needs to be further processed or burnt. Among the typical hot tar removal technologies, thermal cracking at very high temperatures, catalytic reforming, and plasma treatment are usually applied [77].

It is a flexible and robust technology, generally low cost, simple to construct and operate with scale-up potential. Small-scale gasifiers are especially fruitful in applications where the thermal energy, as well as the electrical energy, can be efficiently utilized, and subsequently, their general productivity is high. This technology can be incorporated into a power plant, since it easily allows process integration with existing power production equipment, for example, steam cycle, gas turbines, and gas engines. Gasification additionally restricts the formation of hazardous emissions such as NO_x, SO_x, and heavy metals, and produces residual amounts of sub-products like ash, vitrified slag, and gaseous discharges [29]. Specifically, the combination of gasification followed by combustion has shown a significant reduction in furan and dioxin [78]. The oxygen-deficient environment in the gasifier does not favor the generation of dioxins and furans since they need sufficient oxygen to be formed or re-formed. This, added to the possibility of the production of energy, and chemicals from syngas make gasification an appealing choice for revalorizing plastic waste, the main constituent of MW. However, plastic gasification has the weakness of the high content of tar in the gas product. In addition, since high working temperature requires high operating cost and costly construction materials to work at these temperatures, it is a complex and expensive facility [79].

Many configurations have been designed to optimize the process, such as downdraft fixed bed, updraft fixed bed, bubbling fluidized bed, circulating fluidized bed, entrained flow, rotary kiln, and moving grate [80]. The selection of the gasifier will depend on the particle size, the moisture content, the debris content, the ash melting point, the bulk density, the temperature profile of the gasifier, the heat exchange, the residence time, the conversion efficiency, the process adaptability, etc. [81], [82]. Co-gasification was also studied as a potential thermal technique to obtain valuable products in which the weaknesses of gasification of each type of residue alone can be overcome. For instance, mixtures of biomass and plastic waste keep away problems related to the gasification of plastics alone like feeding complications and the formation of pollutants [83]. [84] used steam gasification co-feeding bio-MW with palm kernel shell obtaining greater efficiency, reduction of char and tar content, and mainly an increase in H_2 production, proving a synergistic effect between the two feeds. Catalytic gasification can also improve the syngas yield as reported by [85], which used ashes from the steelmaking process as a catalyst, obtaining hydrogen-rich syngas from plastic MW feeding. Likewise, [86] employed NiO/g-Al_2O_3 as a catalyst, improving the quality of the gas, which will then use to generate energy from MW from COVID-19.

4.10.1. Syngas

Synthesis gas is constituted of CO, CO_2, H_2, CH_4, higher hydrocarbons, N_2, and impurities. The performance and composition depend mainly on the elementary composition of the waste, LHV of the waste, the amount of injected oxidant, the nature of the gasifying agent, reactor pressure, the temperature gradient within the reactor, the post-treatment of the gas obtained, and the gasifier design [87], [88]. In general, since MW is a heterogeneous feedstock, syngas has a high share of incombustible mixtures, and a lower LHV compared to syngas produced from biomass [89]. Regarding the applications, it can be used directly in the Fischer-Tropsch process for liquid fuel production, in combined cycle gas turbines, internal combustion engines, fuel cells for electricity production, or hybrid systems. It also can be used as a chemical feedstock to make products that substitute natural gas, fertilizers, transportation fuels, and hydrogen [90]. Syngas quality varies depending on gasifier types, temperatures, pressures, feedstock types, particle sizes, gasifying agents, bed materials, and a combination of gasification and other technologies. If necessary, catalytic treatments are employed to enhance the gas quality by increasing the hydrogen quantity and reducing some drawbacks of the process [91]. Catalysts can eliminate or diminish the tar, achieve desired gas proportion, and decrease operational costs. In fact, char could be directly or indirectly used as a catalyst [76].

Separation and purification of impurities are crucial to obtain rich hydrogen syngas. The level of cleanup required relies upon both the nature of the syngas exiting the gasifier and the ultimate utilization of the stream. In this context, it can be referenced venturi scrubbers, wash towers, wet/dry electrostatic precipitators, adsorbing beds or cyclones, fabric filters, and ceramic candles as the most traditional and highly efficient clean-up systems [92].

4.11. Irradiation

Irradiation disinfects waste by exposing it to radiations that are fatal to bacteria. Ionizing radiation such as electron beam (EB), gamma, or ultraviolet (UV), is based mainly on the inhibiting action on DNA of the pathogenic microorganisms [45] (Fig. 6A). It is suitable for fast disinfection and requires a special containment consisting of a concrete bunker, making it difficult to set up in a short time. In addition, it does not produce toxic emissions, or liquid effluent [35]. The use of pulsed xenon ultraviolet light has been of interest for disinfection of the PPE, showing to be effective for the elimination of pathogens [93] but may have questionable efficacy in PPEs having complex geometries. That happens because this method experiences the shadowing effect, which implies that waste surfaces facing the radiation source are more sterile than the waste on the concealed side. In this way, an item with odd shapes, may not be satisfactorily exposed to radiation [27]. Irradiation should not be used in the case of mixed streams containing metals, neither volatile organic substances, mercury, and radiological waste when it is to be treated in electron beam units. On the contrary, it can treat infectious waste including human waste, laboratory waste, and sharps [35]. The efficiency of irradiation is a function of the total energy delivered but it may generate occupational health risks if the person is not protected from radiation exposure [94]. In addition, it is a high-cost technique and there is no decrease in waste volume, so it needs further shredders or grinders.

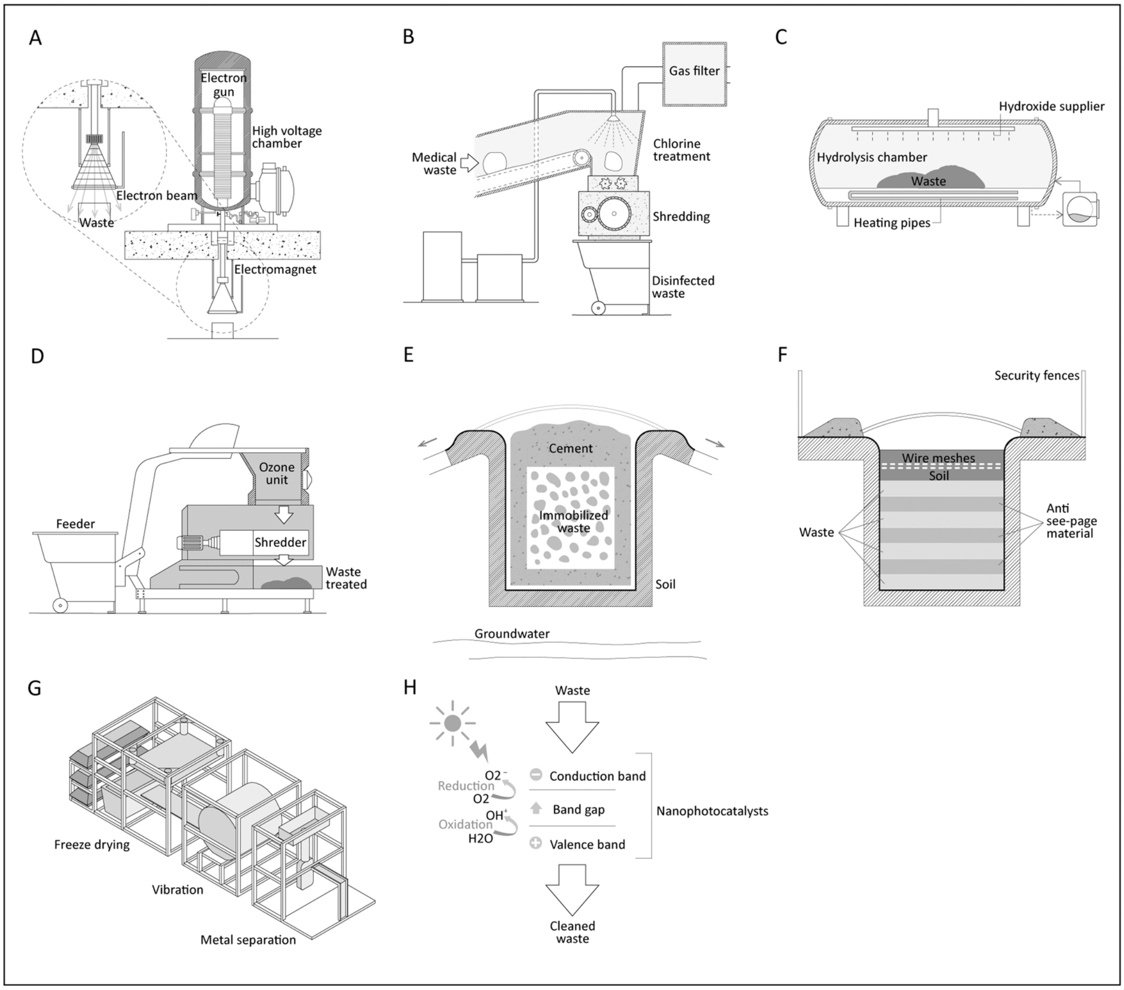

Fig. 6. Diagrams and schemes of physical-chemical technologies. (A) Electron beam (EB) treatment. (B) Chlorine disinfection treatment. (C) Alkaline treatment. (D) Ozonation process. (E) Immobilization treatment [105]. (F) Deep burial. (G) Promession process [109]. (H) Mechanism of nano photocatalysis.

4.12. Chemical disinfection

Chemical disinfection consists in mixing crushed MW with a certain concentration of disinfectant, so it is decomposed, and the microorganisms are killed [1] (Fig. 6B). MW must have sufficient contact area and time with the cleaning agent under negative pressure to ensure the efficiency of the treatment. Then, the exhaust air generated should pass through a series of particulate filters [41]. It makes use of dry and wet disinfectants that require the same treatment, but the disadvantage of using wet chemicals is the presence of residual liquid and waste gas, which can be an environmental pollutant and represents a danger to humans [31]. For dry treatment, the waste volume decrease is higher, and no waste liquid or wastewater and waste gas are produced. Nonetheless, dry waste has higher necessities on the crushing system and the pH value of the activity. This technique is appropriate for liquid MW and pathological garbage, and it is also slowly being utilized for the treatment of MW that cannot be sterilized by warming or wetting. On the other hand, this method is not recommended to treat chemotherapy waste, radioactive waste and volatile and semi-volatile organic compounds, pharmaceuticals, and some types of infectious waste [95]. Especially, it could be considered when the amount of hospital waste is not extensive [42].

Various chemicals are used for the treatment of MW and are selected according to the nature of the waste. The concentration and temperature of the disinfectant are the most important parameters in the process [61]. The chemical disinfection technology can be divided into chlorine- and nonchlorine-based systems depending on the nature of the disinfectant. Sodium hypochlorite was one of the first chemicals used to treat MW, which together with chlorine dioxide are the typical agents used in chlorine-based systems. Although some toxins, like dioxins and chlorinated aromatic compounds, are released when sodium hypochlorite is used, it is active against bacteria, viruses, and spores yet not successful for liquids with high organic content [96]. Instead, chlorine dioxide is a strong biocide, but it is not stable, so it is originated and used on-site. On the other hand, nonchlorine-based disinfectants use either gas, liquid, or dry chemical to treat MW. Among them, H_2O_2 is commonly used in this kind of system.

In general terms, chemical disinfection is fully automated and convenient equipment with good deodorization effects, low air emissions, a fast disinfection process, low investment, low working cost, and a wide sterilization spectrum [48]. It is an effective disinfection treatment because it inactivates bacterial spores and kills microorganisms [87].

4.12.1. Alkaline hydrolysis

Alkaline hydrolysis transforms solid MW into an aqueous solution, adding and stirring an alkaline solution at a certain temperature, so then digestion takes place (Fig. 6C). NaOH and KOH are effectively utilized as alkalies in this method. Despite that either of the two alkalies can be used, a combination of them would improve the efficiency of the operation. The process is also affected by geometry, agitation, time, and temperature. This technology destroys all classes of potentially infectious waste as well as anatomical parts, organs, tissues, and animal carcasses, breaking down organic material into basic amino acids, sugars, soaps, salts, etc. In principle, alkaline hydrolysis can also eliminate many chemotherapeutic or cytotoxic agents, and aldehydes commonly used in hospitals [97], [98].

After digestion, it generates a sterile, neutral solution that is highly nutritious called hydrolysate. It is suitable for release to a sanitary sewer, dehydration for landfill, or use as fertilizer. In addition, it does not create, liberate, or form harmful final products, that is, there is no air contamination or other harmful outflow from this treatment [97].

4.12.2. Ozonation

Ozone is a strong oxidizer and consequently, a strong antibacterial (Fig. 6D). It has the capacity of decoloring and deodorizing. However, an overdose promotes bad smell and secondary pollution [42]. This method requires previous shredding and mixing to expose the waste to this bactericidal agent. After treatment, biological indicators are commonly used to assure microbial inactivation. It can be employed in pharmaceutical waste, water, and air treatment [99], [100]. Ozone does not represent an environmental problem since it is decomposed at high temperatures instantaneously or converted back to oxygen in 30 min under atmospheric conditions [58], [57]. However, since it is toxic and explosive with certain components, it requires further research in the development of the ozonation of solid MW. Also, the operation costs of ozone preparation are high, making it suitable for small-scale applications [42].

4.13. Immobilization

Waste immobilization is the transformation of waste into a compact waste form by embedding, or encapsulation (Fig. 6E). It reduces the possibility of dispersion of radioactive waste during its management, whether handling, transport, storage, and disposal. Encapsulation may include the addition of some chemical substances and is carried out by surrounding the waste with or in an immobilizing material, for example, plastic foam, bituminous sand, cement mortar, or clay, so the waste particles are segregated, and radionuclides are retained. After this process, they are placed into landfill sites to prevent percolation into groundwater [61]. On the other hand, embedding is the immobilization of solid waste by encompassing it with a matrix material to create a waste form without chemical interaction between the waste and the encapsulation medium.

The main immobilization technologies employed are cementation, bituminization, and vitrification. Bituminization immerses wastes into molten bitumen and after cooling, the waste becomes encapsulated [101]. Vitrification is the most used technology for the treatment of high-level radioactive wastes (HLW). Alkali borosilicate glass or alkali aluminophosphate glass are mainly used to immobilize HLW. This process is distinguished by its simplicity and ease. In addition, it is stable enough for disposal, has low leachability, and reduces the mobility of heavy metals [102]. On the other hand, cementation is suitable for the immobilization of low and intermediate-level radioactive waste (LLW and ILW respectively) [103]. Solidification by cementation is mainly used to bind heavy metals contained in incineration ash, so the movement of heavy metals is obstructed [69]. However, the high pH and the content of free water in cement cause corrosion of reactive metals such as aluminum. This process causes an expansion in reaction products and produces a significant amount of hydrogen gas, both of which contribute to immobilization ineffectiveness. A proposed solution is an acid-base cementing system, based on blending calcium aluminate cement with acidic phosphate solutions which have been shown that ameliorates corrosion problems [104]. This is a method that reduces environmental and health risks by diminishing the concentration of hazardous compounds and their toxicity to very low levels. In addition, it keeps personnel safe from accessing the material and from being injured [105]. It has reasonable costs, and it does not require a great deal of skill or knowledge for proper implementation. It is used for pharmaceuticals and incineration ashes with a high metal content as well as radioactive medical waste. A significant drawback is a large increase in mass and volume as well as long-term corrosion issues in cementation if it is not properly managed [106].

4.14. Landfilling

Landfilling consists of burying the trash in the ground and decomposing it into innocuous substances through the long-term decomposition of microorganisms (Fig. 6F). It is generally applied because of its simple operation; low capital cost and a large amount of MW can be processed. However, it requires long-term monitoring of soil and groundwater [40]. Since landfilling is generally operated in open dumps and without previous treatment, it may cause severe environmental concerns like large land occupation, health hazards, risk of virus spread, unpleasant odors, air pollution, and gasses affecting global warming [15], [17]. It produces products in solid, liquid called leachate, and gas phases. Leachate contains toxic substances that may penetrate the soil or reach underground water causing damage to vegetation and water pollution [95]. For that, anti-seepage measures are important to incorporate to not endanger human health or the environment [107]. Windblown dust from dumps can carry pathogens and unsafe materials elsewhere. Piles of refuse during its disintegration process produce some gases, like methane (CH_4), nitrogen (N_2), and sometimes hydrogen sulfide (H_2S). Whenever burnt, carbon dioxide (CO_2) is released. These wastes may also block pipes and open drains, obtrude roadways, damage landscape esthetics, and cause biological pollution. So, it is also necessary to set up gas collection and introduce degassing systems as a means of reducing the negative environmental impact of the biogas produced [108].

4.15. Promession

Promession is a treatment based on freeze-drying using liquid nitrogen followed by mechanical vibration (Fig. 6G). MW, specifically body parts, undergoes cryogenic freezing for around 2 h which takes it to − 196 °C. Then, at that point, it is brittle enough to be crumbled into small particles with the utilization of ultrasonic vibration, which decrease the body to an organic fine substance. The powder is then moved into a vacuum chamber where the remaining dampness vanishes into the atmosphere as steam. Then, the dry powder goes through a metal separator where an electrical current removes any remaining metal like mercury, sodium, or other foreign substances. The rest should be buried safely. This process speeds up disintegration, lessens mass, and volume, and permits the recuperation of metal parts [61]. Promession is an odorless and hygienic process and guarantees the destruction of bacteria and viruses [109].

4.16. Nanotechnology

Nanotechnology has revolutionized the decontamination of bio-MW [98]. Developments in nanomaterials, particularly nano photocatalysts, have been evolving in pharmaceutical and food industries, laboratories, hospitals, and biological and medical applications (Fig. 6H). It represents an effective and reasonable strategy for the decontamination and sanitization of MW applying UV or solar energy to break down microorganisms from waste [40]. It uses the energy from light to produce hydroxyl species and superoxide anions which decompose and oxidize toxic pollutants to carbon dioxide and water [61].

Nano photocatalysts are considered an appealing option concerning energy consumption, and environmental and health issues compared to other MW treatments. Nanostructured photocatalysts exhibit significant attributes such as non-toxicity, low cost, minimum generation of secondary waste, safety, superb stability, high photocatalytic activity, and higher absorption effectiveness in an extensive scope of the solar spectrum [110]. This treatment can be also applied to solid phases like surfaces, gaseous phases, and aqueous treatments. However, removing pollutants using nanostructured catalytic membranes, and nano photocatalysts require more energy and sufficient investment. Additionally, the application of photocatalysis on a larger scale and in actual wastewater systems is still a challenge [27].

4.17. *Thermal plasma technologies*

Plasma is a gas cloud formed by the ionization of inert gas and is characterized as the fourth state of matter, after solid, liquid, and gas (Fig. 7). In the plasma system, power is fed to a torch that has two electrodes, making an arc. Then, an inert gas passes between the two electrodes at extremely high voltage converting the electric energy into heat energy, due to the high resistance of the gas [18]. The system reaches very high temperatures, the waste is rapidly dehydrated, and toxic compounds such as dioxins are disintegrated into innocuous chemical elements [111]. The process produces mixed combustible compounds such as hydrogen, carbon monoxide, and alkanes; but also vitrificated MW or solid slag. The MW should be constantly mixed to guarantee heat and mass homogeneity saving any energetic loss. The heat produced can be recovered for power generation and the solid products can be directly landfilled for disposal after treatment. It is a promising technology for the on-location and off-site treatment of MW [112]. Plasma technology can destroy a big variety of waste such as infectious and hazardous waste, sharps, plastics, chemotherapeutic waste, and low-level radioactive waste, except mercury [35].

Plasma technology releases low pollutant emissions and does not discharge harmful substances, produces low exudation, the potential heat energy can be recycled, achieves a high-volume reduction, reduces the requirements for off-gas treatment because of the high temperatures, and contains high energy density. In addition, it has a quick start-up and shutdown, and a more modest size of installation [112]. On the other hand, the construction and operational costs are very high, and the stability of the system could be easily affected. Energy and material recuperation are accessible ways to reduce treatment costs and increment process efficiency, generating revenues by selling the products such as electricity from syngas. Moreover, thermal plasma technologies suffer a high erosion rate as high current is implemented. There is also a moderated trained community, little process understanding, and an insufficient number of prototype units commercially available which indicates that this technology needs to be further developed [13]. Thermal plasma technologies include plasma combustion, plasma pyrolysis, plasma gasification, and plasma vitrification as described in the next sections [112].

4.17.1. *Plasma combustion*

Plasma combustion is a developed incineration process in which a plasma torch is utilized as a heat source with excess oxygen. This alternative improves combustion at a lower temperature as well as diminishes the air required [113]. However, a high quantity of nitrogen oxides is formed at high temperatures. For that, high amounts of CO and H_2 should be formed because they are efficient reducers of nitrogen oxides [114]. Unlike the classical incineration process, plasma combustion produces dioxins and furans in smaller quantities, and segregation is not needed. Portable plasma incineration with an emission control system can be an attractive solution for on-site treatment [115].

4.17.2. *Plasma vitrification*

Plasma vitrification employs extreme temperatures to produce a glassy and viscous product that solidifies and stabilizes toxic substances. This process is concentrated in smaller installations but consumes significant energy. A high part of non-combustible materials of MW is beneficial for this process. An ideal feedstock would be inorganic hazardous waste such as fly ash since it limits the leaching of hazardous substances like heavy metals, as it would happen if they were deposited in a landfill [116]. This process is present in plasma pyrolysis and plasma gasification. However, the predominance of the vitrification depends on the extent of inorganic components and the addition of additives [112].

4.17.3. *Plasma pyrolysis*

Plasma pyrolysis is the combination of plasma technology with the pyrolysis process. It uses plasma gas to break down a broad variety of wastes using extremely high temperatures with plasma torches of electrodes. This technology reduces the volume of waste significantly, provides good sterilization, and are obtained high-value-added products [117]. Moreover, segregation of hazardous waste is not required, and the number of toxic emissions released is much lower than the limits permitted [13]. On the other hand, a huge capital investment and running costs are needed, and there is NO_x generation and carbon dioxide pollution. It also has high energy consumption and highly corrosive plasma flame prompting incessant maintenance [15]. At the moment it is investigated only at the laboratory scale, although it has attractive characteristics, it still has to overcome several challenges [118].

4.17.4. *Plasma gasification*

Plasma gasification (PG) aims to the destruction of waste utilizing high temperatures breaking the feedstock to molecules in the absence or near-absence of oxygen. PG applied to MW is still in development. This

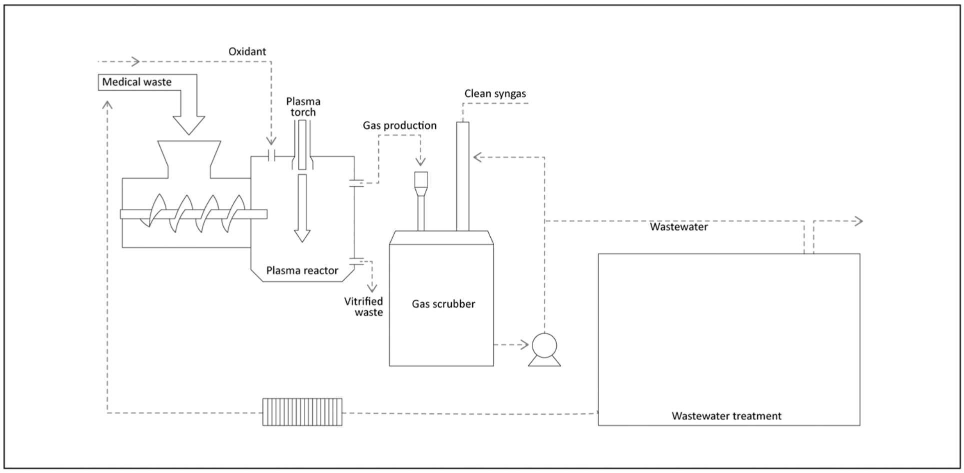

Fig. 7. Diagram of MW treatment using plasma technology.
Adapted from [112].

technology has been especially used for the treatment of various wastes in Japan, Canada, and the USA [111]. Actually, the Japanese MW management organization has recently applied this technology to transform MW into useful products like glass, metal, and syngas [119]. It ought to be noticed that exists just a limited number of industrial-scale plasma waste treatment establishments which have been in activity for certain years, yet the plasma gasification development is further expanding all over the world [111].

Although metals and other inorganic materials can be broken down in a plasma arc, waste that has no net energy content diminishes overall efficiency. Similarly, those containing a high concentration of halogen, require higher operative temperatures and subsequent cooling of exhaust gases [120]. Metals also impact plant efficiency and small quantities are difficult to collect and separate increasing the cost of the process [18]. Like gasification, recovering of energy of syngas once cleaned can produce electricity. Inorganic materials in the feedstock are melted into slag or vitrified glass [81], which is nonhazardous and can be utilized in various applications, like road construction and roofing materials.

PG is a combination of standard gasification with a superior syngas cleaning step [121]. Highly resistant toxins are destroyed, even dioxins and furans, which are the most dangerous toxicants. Thus, the product gas formed in the plasma process is cleaner contrasted with the ordinary gasification and there is no requirement for product gas cleaning [122]. The concentration of tar at the end of the process is the main difference from conventional gasification. It is reported that the tar content is 1000 times lower using plasma technology than the obtained by conventional fluidized gasifiers. The extreme working temperatures, and very high activation energy of PG, makes reduce reaction time significantly [119]. It also raises the calorific value of syngas which is valuable to obtain high-value-added products [112]. In addition, some limitations inherent to conventional gasification such as material yield, energy productivity, dynamic reaction, compactness, and adaptability can be surpassed. Another benefit is that the heating can be modified by adjusting the electrical power provided to the system, making the process more advantageous and independent of the plasma medium [121].

It applies to all types of waste, including municipal solid waste, MW, and hazardous waste [117]. Also, it can vitrify incineration ash and recycle waste at the existing landfill, eliminating the old landfill [123]. On the contrary, the main disadvantage is its heavy electrical power usage. There are numerous costly and energy-consuming steps in the purification of exhaust gases too [124]. In addition, accurate calculation of plasma chemical reactions in the reactor is not possible because of the high temperatures in the reactor and the heterogeneity of the feedstock. Finally, further research is imperative to improve the efficiency of the system and further electricity generation.

5. Power generation

The process of converting non-recyclable waste into energy, either electricity or heat, is called WtE [13]. It represents an excellent solution especially when waste recycling is not economically viable as occurs with medical waste. Albeit the energy effectiveness of a conventional WtE plant is still unsatisfactory, normally going from 14 % to 28 % [125], it is viewed as an essential option in supplanting fossil fuels with environmental-friendly energy sources [81].

It was estimated that the annual global waste generation accounts for 7–10 billion tons worldwide. Only 3 % of them are used for power generation, which indicates that there is considerable potential to be expanded [126]. In this context, thermal technologies are the most appropriate to transform waste into energy. The thermal energy that they produce can be used for electricity and heat production. Among them, pyrolysis, gasification, incineration, and hydrothermal processes have attracted special interest. Specifically, plasma gasification is a moderately new technology that has been analyzed as a solution for WtE recovery with higher thermal efficiencies [29], [121]. The greater part of the enterprises equipped with gasification units, alongside WtE plants, is widespread in Japan since one of the principal objectives of thermal waste treatment comprises the disposal of existing landfills and releasing land for additional utilization. In the European context, Finland is the leader in thermal waste treatment in Europe, providing 57 % of the whole amount to energy-producing use, and has almost completely abandoned any landfill disposal. In the world, just inside the period from 2016 to mid-2019, 161 WtE plants with a total operating limit of 60 million t/y were enlisted. It is predicted that the number of WtE plants will reach 2700 by 2028 at a total operating capacity of 530 million t/y [127]. Yet, large plants are not the most ideal solution if not sufficient feedstock is accessible around. Hence effective, portable, and smaller-scale plants for communities might be noteworthy [76].

Power generation from waste aims to achieve a reduction in environmental pollution, solid waste quantity, and the development of new energy sources contributing to a circular economy. Since WtE power plants can be built close to urban areas, it is also seen a reduction in transportation costs, GHG emissions, and distribution losses. Additionally, it is also possible to use the waste heat from the plant for district heating and cooling (DHC) providing energy in local areas [91].

Various researchers have investigated diverse WtE configurations. For instance, the integrated gasification-power generation cycle is a process in which the product gas is cooled and cleaned by passing through a heat recovery generator (HRSG) and the recovered heat is used to generate steam. The steam from the HRSG can be released or also be sold to consumers for heating districts [128]. [122] investigated the integration of a plasma gasification process with a gas turbine combined cycle to evaluate the possibility of this technology for energy recuperation. The system efficiency was viewed as exceptionally high when it was contrasted with the efficiency of traditional incineration technologies. Another clear example of a WtE system is a plasma gasification facility in Canada that produces power and vitrificates which are utilized as road construction material [129]. Instead, [130] explored heat recovery from MW incineration systems with high reduction of costs. Distinctly, [131] investigated the power generation of a very small power plant from an organic Rankine cycle (ORC) with an incinerator using municipal solid waste and infectious waste. Similarly, [132] analyzed from the energy, economic, and environmental point of view an ORC-incineration system to treat infectious medical waste obtaining positive results and gross electrical power of 23.65 kW. Distinctly, [133] developed an original scheme comprising of plasma gasifier, solid oxide fuel cells, gas turbine, and supercritical CO_2 cycle for power and heat generation. Integration of gasification with high-temperature fuel cells can enhance the efficiency of power generation and optimize the use of waste as a sustainable energy resource through clean energy production (Fig. 8). [134] evaluated the power generation, and environmental impact of treating single-use facemask waste via incineration, concluding that they represent a promising power potential, but incineration would generate serious environmental consequences. Analogously, [135] employed surgical masks to produce electrocatalysts for fuel cells and electrolyzers through pyrolysis, showing a novel route of valorization of waste. [136] designed a novel WtE system based on plasma gasification of MW coupled with municipal solid waste incineration. The hybrid scheme converts MW into electricity reaching a net total power of 4.24 MW.

In this context, a special equipment was designed and built in the region of Piedmont, Italy called Appsterwaste®. It is a converter technology designed by TWM company in collaboration with the Politecnico di Torino that consists of a compact sterilization machine destinated to treat MW and produce energy. The product obtained is an inert and homogeneous fluff, capable of feeding a gasifier to produce syngas. The preliminary tests showed that the valorization of MW, previously sterilized and transformed into fluff, through gasification is feasible. Then, it could be fed to fuel cells (SOFCs or PEMFCs units with a CO clean-up process to reach high syngas quality and consequently, high useful energy [75]). Some initial tests were performed on a laboratory scale with

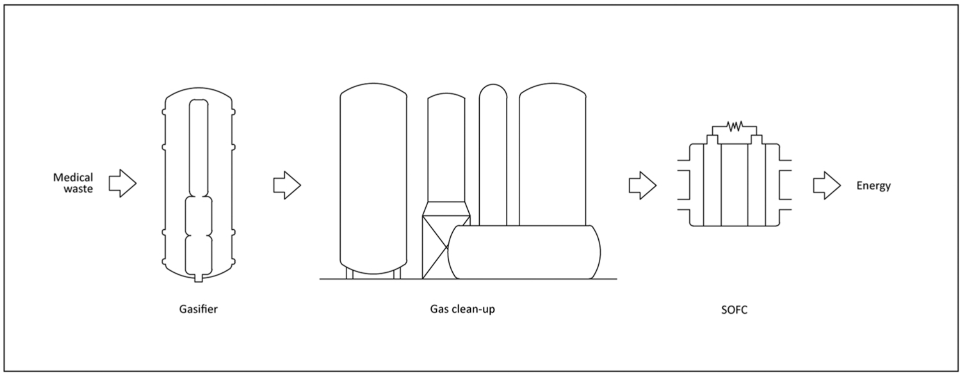

Fig. 8. Example of a WtE process using SOFC.

a fixed bed gasifier to evaluate the quality of syngas obtained. The tests were carried out with steam as a gasifying agent, at different steam-feedstock (S/F) ratios (1, 1.5, 2) and temperatures of 700, 800, and 850 °C. The results are shown in Fig. 9. Increasing temperature, LHV decreases reaching a maximum value of 15 MJ/Nm^3 at 700 °C (Fig. 9C). The opposite occurs with the yield of syngas, which increased with increasing temperature (Fig. 9D). It is also important to note that the hydrogen concentration also increases with the temperature reaching a value of 64 % vol at the maximum temperature tested; while CO, CO_2 and CH_4 experienced a slight decrease (Fig. 9B). On the other hand, the steam/feedstock relationship also plays an important role in the characteristics of the syngas, observing the same effect as the temperature. It is also seen that the CH_4 fraction decreases as the ratio increases, indicating a higher fraction of carbon converted during gasification, as can be seen in Fig. 9A. These results indicate that an increase in temperature and the S/F ratio is favorable to produce a high yield of syngas and hydrogen but are unfavorable for the calorific value that it achieves due to the elevated conversion of carbon, obtaining syngas with a lower LHV. A balance between syngas performance and calorific value is necessary to obtain good quality syngas. These results are the basis for future scale-up and design of WtE plants.

6. Discussion

The generation of MW is increasing, there has been an explosion due to the pandemic that has highlighted the shortcomings of the current management system, even in countries that have good control and administration of their waste, such as Australia [137]. This has reactivated research corresponding to the area and can be seen with the increase in papers published either in the covid or post-covid period. The generation of MW will continue to grow over time regardless of the pandemic, so the improvements to be applied are imminent. This brings with it a large increase in the generation of plastics. The incorporation of bioplastics, and consequently, the reduction of single-use plastics can

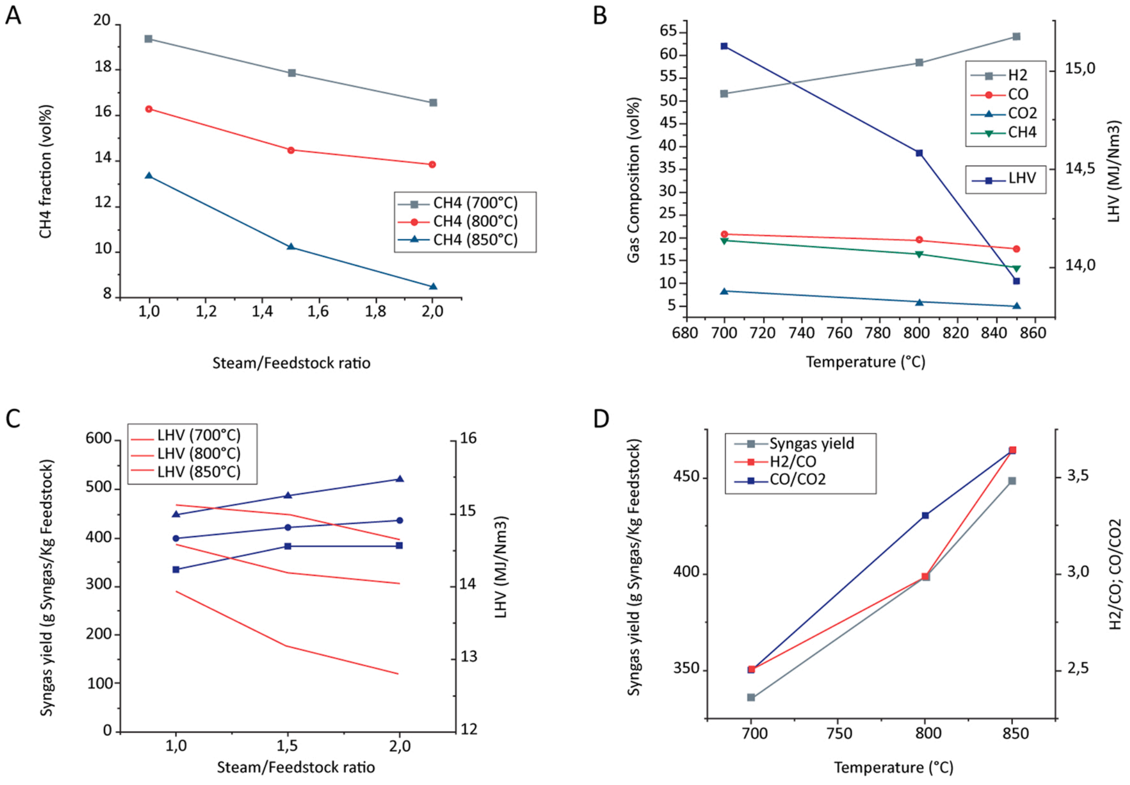

Fig. 9. Characteristics of syngas obtained after treatment of MW and further gasification. (A) fraction of methane vs. steam/feedstock ratio. (B) Composition of syngas vs. temperature. (C) Syngas yield vs steam/feedstock ratio. (D) Syngas yield vs temperature.

have a significant impact since it would increase the amount of recycled material and would prevent the emission of pollutants resulting from its treatment. However, a trade-off between single-use plastics and reused plastics would be necessary in the hospital environment since special attention must be paid to contaminated and toxic materials that cannot be reused.

Although there is a lot of information about proposals and how to improve MW management, the application is scarce. An important investigation was carried out by [138], in which it evaluated the challenges of applying a circular economy in the MW industry. The study concludes that the most relevant factors are the difficulties in reprocessing MW and the lack of a transport and infrastructure system. This implies that there is not only a lack of developing a sustainable process, but also a lack of investment in the sector to create new technologies, new infrastructures, and new management systems. In addition, local regulations and legislation must accompany innovation in the field. And above all, an increase in awareness is necessary to implement new changes [139].

Nowadays, landfill, microwave, chemical disinfection, incineration, and steam sterilization technologies are the typical MW disposal treatments worldwide [17], [13]. Incineration is the most established and used technology worldwide. Therefore, in the countries that produce the largest amount of waste, a high percentage of it is treated by incineration. Among them, Japan stands out, due to its small area allocates around 60 % of its waste to incineration. USA and China also have a high incidence of the use of incinerators. In Europe, the main countries that use this classic technology, representing the destination of at least 50 % of their waste, are Denmark, Norway, and Sweden. In recent times, there is a more sustainable trend that replaces classic incineration. The WtE transition is most notable in incineration, where an attempt is made to recover the wasted energy for the application in turbines and boilers and the consequent generation of electricity and heat. In this scenario, China is installing more and more WtE plants based on incineration, in fact, the largest plant in the world with a capacity of 2.7 million t/y has been built recently. However, in many developing countries without proper management, healthcare wastes are dumped in the open or poorly controlled landfills [112]. Incineration is the most used technology with more than 1,400 incinerator plants worldwide, treating about 59–60 % of them, then 37–20 % of MW is processed by steam sterilization, and finally, 4–5 % by other treatment methods like landfilling, microwaving or plasma pyrolysis [17], [32], [30], [140]. These technologies could be supplemented by pre- or post-treatments like shredders, grinders, and compactors. However, all the techniques available have limits being not able to reduce environmental burden considerably because of toxic gas discharge, large land occupation, impracticality, or economic drawbacks. A precise methodology must be defined to evaluate the viable procedure for MW removal. In addition to the current technical situation, the volume of waste collapsed the current MW management system. In consequence, new facilities must be built to rise capacity. Faced with this situation, mobile units appear as a compelling alternative since they can be arranged in each health establishment, carrying out an autonomous treatment of the waste generated. In this way, collection costs are avoided, the risks of infection during transportation are reduced, and the investment costs of large machinery are reduced. Moreover, through energy use, the treatment could give energy to the establishment for self-supply of electricity or heating.

Table 1 sums up the main characteristics of the technologies presented in this paper, as well as their advantages, disadvantages, applicability scales, and types of MW that can be treated in each case. In general, waste treatment technologies can be grouped as thermal and chemical-physical processes [61], [45]. Thermal treatment technologies can also be classified into low-heat technologies, i.e., between 95 ° and 200 °C (e.g., autoclaves, microwave treatment, dry heat), medium-heat technologies (e.g., reverse polymerization), and high-heat technologies, i.e., over 500 °C (e.g., incineration, pyrolytic incineration, plasma technologies). Low-heat technologies can be utilized for treating infectious waste but are unseemly for chemical, pharmaceutical waste, and anatomical parts without previous mechanical treatment. It results in the deterioration of the properties of the plastics in MW but there is always a danger of forming some toxic fumes during the process [141]. Medium-heat technologies can deal with not just the same waste as low-heat technologies, but also pathological waste. Lastly, high-heat technologies are appropriate for all kinds of healthcare waste, including chemotherapy waste, solvents, and chemical and pharmaceutical waste [105]. On the other hand, chemical-physical processes do not employ heating as means of disinfection. Instead, radiation or chemical disinfectants are used to treat both solid and liquid infectious waste [142]. Among the technologies mentioned, chlorinated compounds, ozone, and UV irradiation are commonly used for hospital wastewater disinfection. While thermal treatments are frequently used for solid hospital waste disinfection [42]. These classifications highlight a critical point, which is that not all technologies can treat all waste. An interesting approach is given by [143], in which it proposed a system based on multiple technologies, where each one treats a certain type of medical waste. In this case, pathological and infectious waste is treated with incineration, then another stream with plastic surgery materials, gloves, etc. is treated with an autoclave, and finally, glass materials produced in hospitals are treated with chemical disinfection. The process is complemented by shredding and water treatment systems. This type of approach can be useful to apply in the installation of new plants, in large dimensions. Thus, all types of MW generated can be treated, without restricting the selectivity of a single technology. The benefits are increased if energy recovery is included.

6.1. Comparison of MW technologies

Open burning and incineration of MW are the worst alternatives since they have a high incidence of global warming and human health damage, especially in developing countries. While incineration causes less contamination to the groundwater or the air than open dumps and obtains high calorific value waste, landfilling leads to huge land occupation, the release of harmful chemicals leachates, and air pollutants, and higher transportation costs due to it being located outside the city. However, landfilling is one of the most economical and practical methods, and if it is properly managed and controlled, causes less CO_2 emissions than incineration [27]. On the other hand, autoclaving and microwaving are economically competitive and have less impact on the environment than incineration, landfilling, and chemical treatment [17]. In this sense, the scale of the waste to be treated is crucial for the selection of the best-adapted technology. Incineration is generally considered to treat large-scale waste, while for small-scale applications less invested technologies or combinations of technologies are used like chemical disinfection or its combination with microwave and steam disinfection techniques [41], [42].

Many researchers have investigated some tools to select the appropriate technology to treat medical waste. Some analytical decision methodologies are multicriteria decision analysis (MCDA), life cycle assessment (LCA) methods coupled with life cycle costing (LCC), Present Worth (PW) method, Delphi method (DM), and energy recovery analysis (ERA) [144]. Table 2 shows some studies which compared different technologies using a determined method to evaluate them. The choice of technology is determined by multiple economic, technical, environmental, and social aspects depending on the methodology employed in each study [145]. Some key elements utilized for technology selection are loading capacity, waste type, environmental emissions and residues, consistency with guidelines, size of the framework and space necessities, a decrease of waste mass and volume, level of automation, technical reliability, health and security considerations, and cost [48]. From the results obtained, it is confirmed that depositing medical waste into a landfill or deep burial without prior treatment is never a convenient option and constitutes the worst alternative. Steam sterilization by autoclave has been chosen in many cases as the most convenient

Table 1
Comparisons among the main technologies to treat MW.

Technology	Advantages	Disadvantages	Characteristics	Suitability	Scale	Ref.
Incineration	- Significant reduction of volume (90%) and weight- Destroys pathogens and hazardous organics - Wide applicability, simple, mature, efficient technology - Heat recovery potential - No requirement for disinfection stage - Unrecognizable waste- Waste sterilized- Suitable for various types of medical waste - Moderate space required - Stable operation- Mature technology - Mobile incinerators potential for on-site treatment	- Large installation - High investment and operation cost - High testing and repair costs - Air emission control problems. Possibility of producing harmful or corrosive gases - High demand for excess airflow- Hazardous solid output, fly ash, and bottom ash with toxic metals- Work at lower temperatures - High CAPEX- Release of secondary pollutants like dioxin and furans- Public opposition - Need regular maintenance and special monitoring - Short life span - Skilled operator needed - Expensive control equipment is required to reduce emissions	- High temperature (980–2000 °C)- Excess oxygen- Products: ash, flue gases, particulates, heat- Off-site treatment- Mobile incinerators to on-site treatment	All types of waste but not recommended for pressurized gas containers, reactive chemical waste, silver salts, PVC plastics, heavy metals, sealed ampoules or vials, radioactive materials, and unstable pharmaceuticals	Large-scale applications	[32,33,35,61,63,64]
Steam Sterilization	- Operation safe and reliable- Mature and flexible - Fast rate of processing - Good adaptability for MW quantity variations.- Operation at saturated steam that does not generate toxic waste- Good sterilization- Strong penetration- Well-established technology- Ease of biological testing- Low-hazard residue- Low investment and operation costs	- Air emissions. It is easy to produce volatile organic compounds, carcinogenic compounds, and mercury fumes - No considerable volume reduction. It needs further crushing -Effluents have certain toxicity, are needed additional purification treatment - It requires strict classification management of medical waste - Inability to change the waste appearance - Remained waste must be landfilled - Possible incomplete disinfection -	- Low-temperature treatment - Autoclave/ hydroclave/ chemiclave - Biological monitoring	Infectious waste, laboratory waste, and medical waste but not suitable for pharmaceuticals, radioactive and pathological waste	From small to large-scale applications	[32,36,38,39,50,51,53,54,56]

(continued on next page)

Table 1 (*continued*)

Technology	Advantages	Disadvantages	Characteristics	Suitability	Scale	Ref.
		Requires technical staff - Not applicable to huge amounts of hazardous waste - Requires significant energy				
Microwaving	- Low process temperature economizes energy - Low contamination without gaseous emission - Mobile microwave treatment facility is appealing to on-location treatment - High efficiency- Absence of liquid discharge - The emissions are minimal - Rapid action (short heating time) - Low heat loss- Selective heating - No direct contact with materials - Easy to operate	- Relative tight range of sanitization, in some cases should apply with an autoclave - Complex impact factors of disinfection - Huge capital investment, high running cost - Need regular maintenance - Remained waste must be landfilled, and wastewater should be treated - Possible incomplete disinfection - Offensive odors - Needs a shredder	- High-frequency short waves- Batch or semi-continuous- On-site or mobile treatment	Infectious and pathological waste (except human organs, infectious animal's carcasses, etc.) but not suitable for cytotoxic, volatile compounds, body parts, large metal items, dangerous chemicals, and pharmaceutical waste	Small or medium scale	[46,62-64]
Reverse Polymerization	- Variable energy input	- Shredding should be applied to reduce the volume - Requires a scrubber to control emissions - Wastewater produced should be treated - High costs - Negative public acceptance	- Nitrogen-rich atmosphere - Moderate temperature - Application of microwave energy	Infectious waste including biological and anatomical waste, needles, sharps, plastics, and glass.	Small or medium scale	[35,48,66]
Nanotechnology	- Non-toxicity - Low operational cost - Minimum generation of secondary waste - Safe and stable - High absorption efficiency	- Requires energy - High investment - Applicability to wastewater is still challenging	- UV or solar energy - Photocatalysts	Pharmaceuticals and infectious waste, wastewater, surgical masks hospital surfaces	Lab scale	[27,31,40,71,72]
Chemical disinfection	- Rapid and stable performance - Broad sterilization spectrum - Low air emissions - High efficiency - Waste deodorization - Low investment and low operating costs - A fully automated technique - Simplicity to release liquid effluent into the sewage - No by-products of combustion detected - Rapid disinfection	- Does not reduce volume and mass - High agent costs - Wet disinfectants produce toxic gases and liquids - Residual disinfectants - Need for chemical storage and use - Possible incomplete disinfection - Needs a shredder	- Disinfectant penetrates the waste - Sufficient contact area and time - Dry or wet treatment	Pathological waste but not suitable for chemotherapy waste, radioactive waste, and volatile and semi-volatile organic compounds, pharmaceuticals	Small to medium-scale applications	[41,48,51,63,67,79,87]
Alkaline hydrolysis	- Generates a sterile and neutral solution - Hydrolysate used as fertilizer - Does not	- Effectiveness affected by geometry, time, and temperature	- Digestion - NaOH and/or KOH agents	Chemotherapeutic, cytotoxic agents, infectious agents such as anatomical	Small-scale applications	[82,98]

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Table 1 (*continued*)

Technology	Advantages	Disadvantages	Characteristics	Suitability	Scale	Ref.
	produce harmful end products			parts, organs, tissues, animal carcasses		
Ozonation	- Capacity of decoloring and deodorizing - Ozone is decomposed instantaneously	- Needs previous shredding - Ozone is toxic - High costs	- Ozone - Biological indicators	Pharmaceutical waste, water, and air treatment	Small to medium-scale applications	[57,58,63,88,99]
Pyrolysis	- Increased energy efficiency - Auto-thermal conditions - Generation of value-added products - The lack of oxygen prevents dioxins and furans formation - Energy saving and reduction of waste volume- Adaptability to different conditions - Low carbon discharge - No requirement for disinfection stage - Heat recovery potential - Smaller cost than incineration - A catalyst can be added - Less harmful substances produced - Co-pyrolysis improves oil quality	- Air emissions. Combustible gases raise security concerns and strict controls are needed - Pollutants like NO_x, SO_2, char, tar, ash, etc., need to be removed - High investment costs - Need further research (developing technology) - Skilled operator needed - Pre-treatment is required - High energy consumption - Not easy to achieve stable combustion	- Endothermic process - Complete absence of air - Does not include a reactive step - Products: char, oil pyrolysis, and syngas	All wastes are normally treated in an incinerator. Sharps, materials contaminated with blood and body fluids, surgery wastes, laboratory waste, soft wastes (gauze, bandages, drapes, gowns, bedding, etc.), plastics, blood and body fluids, pathological waste, animal wasted dialysis waste, chemotherapeutic waste, pharmaceutical waste, hazardous waste. Not recommended for radiological wastes and waste contaminated with mercury	Small to large-scale applications	[73,75,86,97,99]
Gasification	- High energy efficiency - Low emissions - Auto-thermal conditions - Generation of value-added products - No requirement for disinfection stage - Suitable for syngas generation - Robust technology - Scale-up potential - Flexible feedstock- Prevents the formation of hazardous emissions - Catalysts can be added - Co-gasification can improve syngas quality	- Production of combustible gases which raise a security concern, and strict controls are needed -Pollutants like NOx, SO2, char, tar, ash, et., need to be removed - Requires a high amount of energy - Complex and expensive facility	- Endothermic process - High temperature (600–950 °C) - Oxygen deficiency - Syngas production - Multimodal products	All wastes are normally treated in an incinerator. Sharps, materials contaminated with blood and body fluids, surgery wastes, laboratory waste, soft wastes (gauze, bandages, drapes, gowns, bedding, etc.), plastics, blood and body fluids, pathological waste, animal wasted dialysis waste, chemotherapeutic waste, pharmaceutical waste, hazardous waste.	Small to large-scale applications	[83,101-107]
Thermal Plasma	- High operation temperatures and energy densities - Compact reactor geometry (modest size of the establishment) - Autonomous energy input - Decreased gas flow and pre-requisites for off-gas treatment - Quick warming, start-up, and close-down periods - Not require segregation - Potential energy recovery - High volume reduction - Low exudation- Treat any form of medical waste - Low pollutant emissions	- High energy consumption - Refractory material may be needed due to the high temperature - Limited lifespan of the plasma torch with electrodes - Requires technical persons - Cost is very high - The stability of the system is easily affected -High erosion rate	- Plasma state - Very high temperature - on-site and off-site treatment - Products: Syngas, vitreous solid	All types of waste, Infectious waste, sharps, plastics, dialysis waste, hazardous waste, chemotherapeutic waste, low-level radioactive waste	Large-scale applications in development – Lab and pilot scale	[112-114,116,117,118,121,124,125]

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Table 1 (*continued*)

Technology	Advantages	Disadvantages	Characteristics	Suitability	Scale	Ref.
Torrefaction	- High energy density product - No necessity for disinfection stage - Low debris and sulfur content - Low carbon release- Solid product easy to transport, manage, and storage - Excellent grindability, hydrophobicity, and stability - Simple and mature	- Deficient operating conditions to facilitate further degradation - Probability of delivering harmful or destructive gasses	- Inert atmosphere - Intermediate temperature (200–300 °C) - Product: char - Low moisture content	Plastics	Small to large-scale applications	[53,54,91]
Wet Carbonization	- No prerequisite for the sterilization stage - Low carbon discharge - Low ash product - Able to eliminate chlorine content from PVC proficiently - Potential for recovering nutrients from the liquid	- Requires addition of water to MW - Requires washing and drying of the product - High energy utilization for pressurization and warming - Difficulty in continuous process - Requires high -pressure reactor - Batch process	- Product: hydrochar - High moisture content	Biomass, plastics	Small to large-scale applications	[51,56,84]
Immobilization	- Reduces migration or dispersion of radionuclides and heavy metals since they are contained in the matrix - Simple, stable - Prevent leachability - Reduces the concentration of hazardous substances and toxicity - Not expensive - Not require special skills	- Corrosion in cementation - Large increase in mass and volume		Pharmaceuticals, incineration ashes, radioactive waste	Small to medium scale	[41,42,44,45,46,106]
Landfill	- Simple and mature technology - Low cost - Easy operation - A large amount of MW can be processed - Short-term solution	- Risk of virus spread - Large land occupation - Poisonous gases emissions, dusts generation - Cause soil pollution and water contamination - Needs anti-seepage measures - Strict pretreatments and previous disinfection are required - Long-term monitoring of soil and groundwater is required -Unpleasant odors	- Long-term decomposition of microorganisms - Off-site treatment - Land disposal - Impermeable	All hospital waste with the previous pre-treatment	Large-scale applications	[15,17,33,95]
Irradiation	- Industrially tested sterilization technique - Safe and reliable technology - Treatment in the same original containment system - Not emissions or effluents are generated - Fully automated and	- High initial investment cost - High voltage and radiation risks - Occupational health risks - Difficult to control process efficacy - The presence of	-EB-UV-gamma - Efficacy dependent on the energy delivered	Infectious waste, laboratory waste, soft waste, and sharps but not appropriate for metals, volatile, semi-volatile organic natural mixtures, mercury,	Small to medium scale	[59,84,93]

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Table 1 (*continued*)

Technology	Advantages	Disadvantages	Characteristics	Suitability	Scale	Ref.
	easy to operate - Fast disinfection	metals not ground produces shadow areas affecting the homogeneity of the treatment - Difficulties to realize mobile plants - Low public and social acceptance - Bad smell - Questionable efficacy in complex geometries- Not reduction in volume		radiological and pathological waste		
Dry heat treatment	- Low investment and operational costs - Non-corrosive - Does not involve toxic agents - No human intervention, easy to use - Heat can go deeply into thick objects	- Can take much time to achieve sterilization - Dangerous chemicals can remain in the solid or escape into the air - Some offensive odors may be released - Considerable power expenditure	- Hot air ovens - On-site treatment - Conduction, convection, and radiation	Metals, sharps, and soft wastes (gauze, bandages, gloves, etc.) but not suitable for volatile and semi-volatile organic compounds, chemotherapeutic wastes, mercury, other hazardous chemical wastes, radiological wastes, and human or animal body	Small scale	[28,49]
Converter technology	- Compact size - On-site treatment - Clean and chemical-free - Economical - Not produce hazardous emissions or radiation - Pre-treatment and main treatment in the same unit - Short time of operation - Significant reduction of volume and weight - Safe	- Demanding maintenance	- Compact unit - Cycle of 30 min - On-site treatment - Steam sterilization	Surgical waste, infectious waste, needles, sharps, masks, plastics, pharmaceuticals	Pilot scale	[20,74,75]
Bio converter	- No power requirement - Minimize GHG emissions - High flexibility - Recovery of recyclables, RDF, and biogas production	- Odor nuisance - Time-consuming	- Solution of enzymes	Biodegradable plastics	Lab scale	[60,76]
Promession	- Speeds up the disintegration - Reduces mass and volume - Permits recuperation of metals - Odorless and hygienic - Guarantees destruction of bacteria and virus	- Not commercially available - Negative public acceptance	- Freeze-drying treatment - Vibration - Metal separator	Body parts	Small scale	[31,109]

technology among the reported comparisons. This is because autoclaving is a friendly technology from an environmental point of view, the operating costs are not excessive, and it achieves a good degree of sterilization of a wide range of products. Based on this, mobile steam sterilization machines can be considered the best solution in the short term to be incorporated in healthcare centers due to the wide acceptance, fast installation, and feasibility of the process [146]. However, when the energy recovery factor is considered, incineration becomes relevant. Although there are not many comparisons between thermal technologies reported in the literature, when incineration is compared with gasification or pyrolysis, the most convenient option is reduced to the last two. This means that thermal technologies are more favorable than the rest when the energy can be used for new processes, and if an efficient control/reduction of emissions is added, it would be the most convenient option for future applications.

Pyrolysis is a step behind compared incineration and gasification, principally at a research and pilot-scale level because of the unstable control of the reaction process to optimize the products generated [15]. However high temperature pyrolysis has a wide range of applications and good economic benefits. For example, pyrolysis gas produced by the waste can be utilized to impulse energy circulation in a medical waste pyrolysis installation [147]. In addition, [148] compared the energy

Table 2
Technology selection based on the methodology employed.

Technologies compared	Methodology	Technology selected	Ref.
Incineration-landfill-microwave-steam sterilization	VIKOR-based fuzzy multi-criteria decision-making (MCDM) model	Steam sterilization	[162]
Steam sterilization-chemical disinfection -pyrolysis	LCA - LCC	Chemical disinfection	[95]
Microwave-incineration-autoclave-landfill	MCDM model (DEMATEL and TOPSIS)	Steam sterilization	[163]
Steam sterilization and landfill with/without energy recovery -incineration with/without heat recovery	LCA	Incineration with energy recovery	[164]
Steam sterilization-microwave-lime disinfection	LCA - PW method	Microwave	[165]
Incineration with/without heat recovery-steam sterilization-microwave	LCA - LCC - Delphi method	Incineration with heat recovery	[166]
Hydroclave-autoclave-chemclave	Laboratory examination	Autoclave Chemiclave	[167]
Incineration-steam sterilization-microwave-plasma pyrolysis-promession -chemical disinfection-encapsulation-autoclaving and retort-landfill	fuzzy VIKOR/TOPSIS MCDM	Incineration	[168]
Rotary kiln incineration-pyrolysis-plasma melting-steam sterilization-microwave	ERA LCA LCC	Rotary kiln incineration Microwave Pyrolysis	[169]
Autoclave-chemical treatment-microwaving-deep burial-incineration	MCDM (HF-SOWIA and MOOSRA)	Autoclave	[170]
Steam sterilization-microwave-landfill-incineration	fuzzy MCDM model (OWA)	Steam sterilization	[171]
Incineration vehicle-movable steam sterilization-movable microwave (+ co-incineration)	LCA	Movable steam/microwave (+co-incineration)	[172]
Incineration-microwave-landfill - on/off-site steam sterilization	MCDM model (ANP and ELECTRE)	Off-site steam sterilization	[173]
Incineration-autoclave-microwave	Sustainable Assessment of Technologies (SAT) methodology	Incineration	[44]
Incineration-landfill-hydrothermal carbonization	LCIA - economic comparison	Hydrothermal carbonization	[51]
On-site incineration- on-site incineration + microwave-microwave-expanded incineration	survey - interview	On-site incineration + microwave	[32]
Converter - ozonator - Autoclave	PW method	Ozonator	[58]
Autoclave - incineration - microwave	eco-decision support model (eco-DSM)	Autoclave	[174]
Incinerator-microwave-vitrification-autoclave-chemical disinfection-landfill	Fuzzy eco-DSM	Vitrification	[175]
Incineration-microwave-chemical disinfection-reverse polymerization-steam sterilization	analytic hierarchy process (AHP)	Steam sterilization	[151]
Gasification/pyrolysis-rotary kiln incineration	LCA	Gasification/pyrolysis	[176]
Incineration-autoclave-microwave-chemical disinfection-hydroclave	survey - interview	Autoclave	[154]
Hydroclave - autoclave-dry heat treatment-chemical disinfection	Decisión tree analysis	Autoclave	[159]
Incineration - steam sterilization-microwave - landfill	MCDM by using intuitionistic fuzzy (IF)	Incineration	[177]
Incineration disposal vehicle - steam sterilization - movable microwave - Co-incineration with hazardous waste - Co-incineration with MSW waste	LCA	Movable microwave Steam sterilization	[178]
Incineration with energy recovery, autoclaving, chemical disinfection, and shredding – Incineration, autoclaving, chemical disinfection, and shredding	LCA	Incineration with energy recovery, autoclaving, chemical disinfection, and shredding	[143]
Incineration – autoclaving – chemical disinfection	LCA LCC	Autoclaving Chemical disinfection	[179]

content of the different products obtained after being treated MW by different technologies, and it turns out that the products obtained from pyrolysis, especially the gas and liquid phase, are the ones with the highest energy value, around 40 MJ/Kg, compared to hydrochar, solid obtained by torrefaction, and even the products generated by incineration and gasification. This means that pyrolysis has great energy and economic potential for the valorization of the end products. Combinations of pyrolysis and gasification technologies were also evaluated since this integration improves the thermal efficiency, the quality of syngas, and tar removal. For instance, the Viking gasifier [149] is a two-stage process in which pyrolysis and char gasification occurs in two separate reactors. Thus, the gasifier acts as a tar-cracking unit. Pyrolysis and gasification have been the focus of research in recent years, since, unlike the rest, not only is it possible to recover energy, but it also allows the valorization of MW through the generation of by-products of industrial importance, such as syngas, char, and tar.

These technologies in plasma conditions have superior advantages. The high temperatures employed in a plasma accelerate the chemical reactions and produce some reactive species that are unreachable to get by conventional methods [121], but currently, there is a lack of infrastructure for widespread adaptation of this technique [150]. Among them, plasma gasification displays minor environmental impacts in terms of air emissions and leachates as compared to other WtE processes. Actually, [151] compared plasma gasification to incineration exhibiting higher efficiencies and enhanced power production for the plasma technology. Similarly, [152] contrasted plasma gasification and incineration in different settings. As a result, plasma gasification is preferable for power generation, generates greater economic benefits, and has better environmental performance. A hybrid process could be also implemented, like a plasma process combined with incineration or some other thermal process offering better use of the calorific content of the wastes [122]. Plasma technologies offer innumerable advantages in comparison with other methods, but the main problem is the enormous consumption of electricity and the cost that it implies.

6.2. TRL analysis

TRL evaluates the maturity of a particular technology, but also it enables the comparison of maturity between different types of technologies. TRLs provide a common understanding of the status of a technology in its development pathway, and a means of decision-making when funding or implementation of a technology is considered. TRL associates integers (1–9) to the technology as it progresses from an initial idea to commercialization [153]. TRL stages are summarized in Table 3.

As can be seen in Fig. 10, all the technologies mentioned to treat MW are classified according to the TRL. Each technology is considered an independent case, not comparable with the others in terms of transition costs or capacity. The most popular commercially available technologies, with a TRL 9, are incineration, landfilling, microwaving, chemical disinfection, and autoclaving. There are also other treatments well-established in the market such as immobilization, and deep burial, but also irradiation, alkaline hydrolysis, and dry heating for smaller scales. The rest of the technologies are a step behind and need further development and optimization. Although numerous investigations are being carried out with gasification and some countries are beginning to implement it, there are still some obstacles related to the formation of tar, and the use of syngas for its free commercialization. Reverse polymerization is a method that is used industrially in other areas, but it still must optimize the costs and the plastic pre-separation process. There are very few cases applied to MW in the case of dry/wet carbonization and they are at the pilot scale. This is possibly due to the low commercial value of char/hydrochar which must be improved, possibly using co-treatment techniques with other types of waste to increase energy value and reduce costs. Converters are a very convenient option, and possibly one of the best for treating small-scale medical waste. A few prototypes were created, and some of them are used in hospitals and health centers. The biggest obstacle to overcome is related to the scale-up and the use of the fluff generated for further processes. There are many studies using plasma as a thermal method to treat waste. Many of them are on a pilot scale. The biggest drawback is the high costs involved in the process and its manufacture. Plasma gasification is one step ahead of plasma pyrolysis. The same is concluded with classical pyrolysis. Pilot scale tests are still being carried out to obtain a liquid of high commercial value. There is almost no research using promession as a treatment. Very few pieces of equipment built on a pilot scale are reported. Possibly it is due to the high costs involved in the process, as well as the low applicability. Bioconversion is an interesting option that is rarely used to treat agricultural waste, but for MW it is still in the R&D phase. Similarly, methods using nanotechnology are relatively new and are on a laboratory scale, so further research is still needed.

Table 3
Technology Readiness Level (TRL) framework.

TRL	
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

Source:Adapted from [180].

As mentioned, some obstacles must be overcome for the development of thermal technologies, such as the development of a gas treatment for torrefaction, the development of continuous processes for wet carbonization, further optimization of the pyrolysis process, treatment of the gases produced in incineration, and technologies for elimination of tar for gasification, in addition to developing greater heat integration systems to increase the efficiency of the process [53]. However, this analysis allows us to see the progress, and how the development of technologies is evolving toward more sustainable options.

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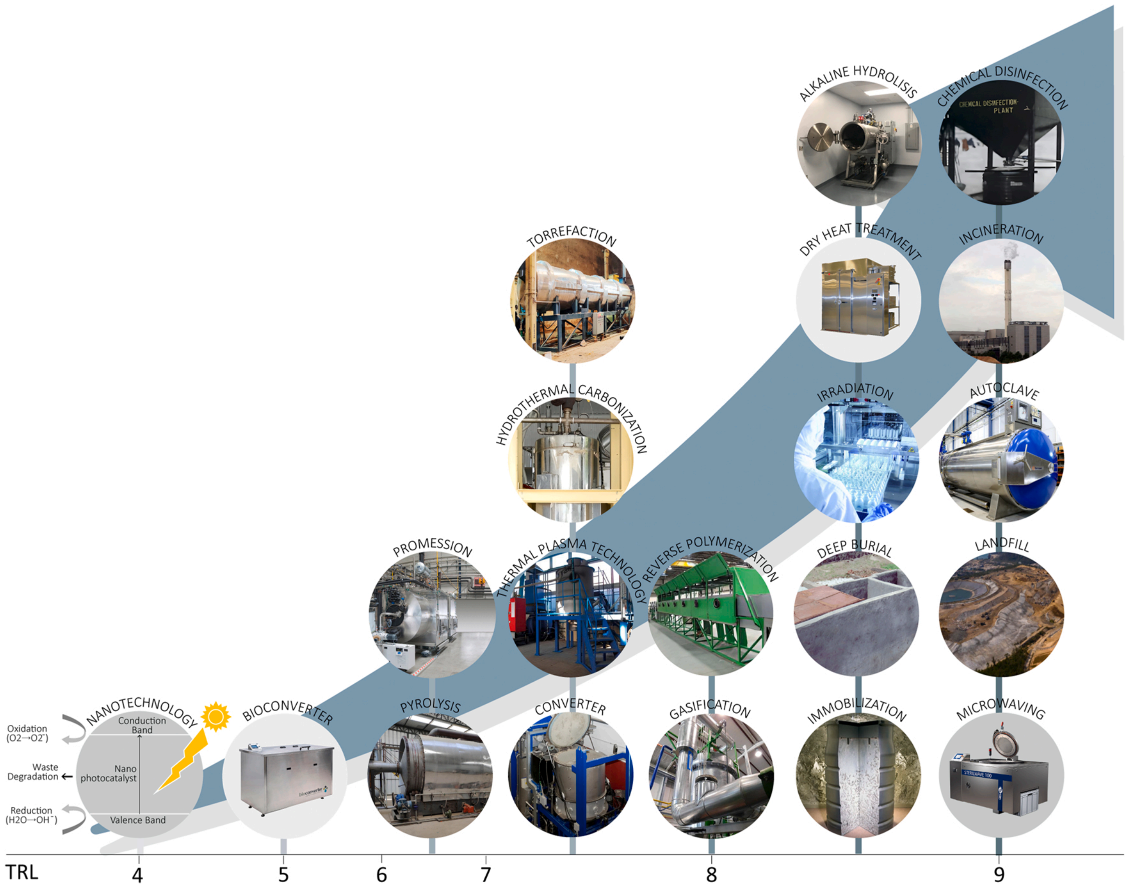

Fig. 10. TRL classification for MW technologies.
Source: Images were retrieved from open data sources

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6.3. *Economy*

Technical, environmental, and social aspects are important, but the cost of the technologies determines the feasibility of their application, both the initial investment and the operating costs. Capital costs for huge frameworks should incorporate transportation, import duties, site planning, installation, commissioning, project management, and administrative fees. Operating costs include labor, utilities, supplies, maintenance, and periodic validation testing [28]. Costs of disinfection, personnel protection elements, and training should be also considered [11]. However, the implementation of a given technology is only one part of the entire chain of waste management. It was estimated that the total costs for the management of regulated medical waste (RMW) or infectious waste are about five times more expensive than those of non-regulated medical waste (NRMW) or municipal solid waste [32]. This points out that correct segregation at hospitals would significantly reduce the total costs of the treatment of MW as well as hazardous emissions. Although transportation costs are elevated, the cost of the MW recovery and recycling remains the main bottleneck in the entire process [31].

Treatment costs not only depend on the process itself but also on extrinsic variables like geographic location, quantity, the composition of waste, etc. Regarding incineration, the operation is not costly but training the personnel, constant monitoring of pollution, transportation of the final ashes to appropriated landfills, and the incorporation of new APC to reach air emission standards increase the total cost of the incineration process [36], [154], [142]. It was reported that the cost varies from 0.7 to 1.1 €/kg [45]. Developing an efficient heat recovery system from incineration is an alternative solution to reduce costs and even generate profits from wasted energy.

Since incineration is the main technology used worldwide, numerous studies have been conducted comparing it with other emerging technologies to assess their viability. Pyrolysis reported lower operating costs than incineration. It requires a more modest air coefficient, so the amount of flue gas delivered is decreased and the required flue gas cleaning device is smaller [40]. Otherwise, the capital cost of installing an alkaline digestor can be as low as a fifth of the cost of a new incinerator [98]. Incineration was also compared with landfilling. The cost of landfilling is not minor in comparison with the other processes, detailing that the investment cost for the construction and the operating cost is determined as around 20 €/t and 0.3–0.6 €/t, respectively [154]. Next, hydrothermal carbonization for processing MW is economically competitive with incineration. Among the products obtained by HTC, hydrochar from MW is the most valuable. It has a heating value ranging from 2.72 MJ/kg to 38.3 MJ/kg which makes it very attractive to be used as fuel. However, the selling price of the pelletized hydrochar is still higher (162 €/t) than coal (48 €/t), which means an obstacle to its commercialization [51].

Plasma technologies are more expensive than other thermal techniques. Investment costs are elevated due to the extreme temperatures, special materials of construction to endure the medium conditions, level of automation, costs of the plasma source, and limited technical experts in plasma technologies. Operational costs are also costly because of the high-power consumption and frequent maintenance, even greater than incineration [155]. It was estimated that, for example, a plasma gasification plant with a capacity of 500 t/d has an investment cost of about 56–172 M€ [156], much higher than a pyrolysis or gasification plant, which was estimated at 75 M€, and 69 M€, respectively [157]. This, added to security issues make this technology less interesting for investment. This technology is not yet very widespread, counting that only is used commercially at five locations around the world. Thus, it should surpass some challenges to be expanded not only at lab or pilot scales. The costs could be reduced by process integration, process intensification, getting revenues from syngas, and improving power efficiency [124]. For example, in Makkah, a project was proposed in which the plasma pyrolysis method for energy recovery is evaluated. In it, considerable profits are obtained from the electricity produced by treating MW from hospitals, which makes the process more convenient [158].

Some authors affirm that the autoclave is the most cost-effective technology for the disinfection of healthcare wastes [159]. It was reported that the investment cost of autoclaving is considered in the range of 100.000–200.000 € and the operating cost is approximately 0.1 €/kg [154]. However, the microwave could be convenient from an environmental and economical point of view, for small healthcare facilities [160]. Combined technologies are also an appealing option, like microwave-assisted pyrolysis which presents a superior economic advantage because of the diminishing in operational costs and heating time compared to conventional technologies such as incineration, landfilling, and gasification [161]. Finally, the costs of chemical disinfection mainly depend on the quantity and type of disinfectant [42].

Due to the great variability of prices, details of all the technologies mentioned have not been found. In addition, there are technologies under development, which are not yet possible to obtain a clear technical-economic approach but are alternatives that deserve further investigation. However, the biggest problem is in the management of medical waste. The lack of standardized separation and distribution procedures creates inefficient waste management that directly affects total costs. Concerning treatments, it has been reported that electricity is the biggest factor that affects the cost of technology, which is why plasma-based technologies are the most expensive. The incorporation of the WtE concept helps reduce costs, optimizing the resources necessary for operation. Likewise, the production and sale of by-products imply an extra benefit that contributes to the eco-efficiency of the process. The combination of technologies has been shown to increase energy efficiency, thereby increasing energy recovery, and lowering process costs. Conventional technologies, such as incineration and landfill, are not only harmful from an environmental point of view but also economically. Even when the costs of thermal technologies have been compared, incineration is still at a disadvantage, with pyrolysis, gasification, or hydrothermal carbonization being the most favorable.

7. Conclusion

This theoretical study presented the current scenario of solid medical waste disposal. Although the main problems that generate the mismanagement of MW are related to the lack of capacity, transport logistics, standardized procedures, trained workers, and uncontrolled discharge of pollutants into the environment; they represent the main focuses of improvement. These starting points establish the core of regulations and policies to be applied for the adequate management of MW.

Based on the comparative study of current technologies and the TRL analysis carried out, further optimization of existing technologies, and innovation are still needed. Although extensive development is still necessary, this paper details the research trends in MW technologies, and draws on the theoretical bases to select an appropriate technology according to the characteristics of the MW. Some energy recovery options were also raised since the reduction of energy consumption is imperative, and these techniques, together with the production of useful end-products are appealing alternatives to existing thermal technologies. The use of renewable energy sources in MW treatments is an emerging choice still immature with few studies published to date. Hybrid systems and co-processing of MW with other wastes deserve deeper evaluation, as they may contribute to creating higher value-added products. Meanwhile, the incorporation of mobile technologies for on-site treatment can represent an ideal solution for emergency situations. Research directions for this field can be developed with the help of this study towards a more efficient treatment, with less impact on people's health, eco-sustainable, attainable, and adaptable for all countries.

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.

Data availability

No data was used for the research described in the article.

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