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Mini-review Article

WM&R

Waste Management & Research
2017, Vol. 35(5) 471–479
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sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0734242X16684385
journals.sagepub.com/home/wmr
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Microwave as an emerging technology for the treatment of biohazardous waste: A mini-review

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Abstract

Microwave is an emerging technology to treat biohazardous waste, including material from healthcare facilities. A screen of the peer-reviewed literature shows that only limited information may be found in this area of work and, furthermore, analysis of the references reveals that sometimes not all necessary aspects for the appropriate use of the technology are considered. Very often conventional microwave technology is applied for the inactivation of pathogens, which might make sense for certain applications but, on the other hand, may lead to the misbelief that microwave systems cannot be used for the inactivation of a solid "dry" waste. However, conventional microwave units have no means to control the inactivation process, and especially moisture content. But there are a few sophisticated microwave technologies with appropriate measurements allowing a validated inactivation of biohazardous materials. These technologies are an effective tool for inactivation and some of them are commercially available. It must also be considered that the waste should be preferably inactivated either directly at the place where it is generated or biohazardous waste should be transported only in closed systems. Moreover, microwave technology presents a possibility to save energy costs in comparison to the more widely used autoclaves. This mini-review will discuss important aspects for the use of microwave technology for the treatment of biohazardous waste.

Keywords

Microwave, inactivation, disinfection, biohazardous waste, healthcare waste, carbon footprint, microwave-assisted technology, mini-review

Introduction

The main benefit of microwave energy is the direct delivery of energy to microwave-absorbing materials, which allows the volumetric heating of samples. Issues such as long heating periods, thermal gradients, and energy loss to the environment can be minimized (Bélanger et al., 2008). These attributes of microwave energy make it very attractive for industrial applications as an alternative to conventional processing methods.

With respect to food or beverage processing, one of its applications is green tea. When green tea manufacture was compared by parching, steaming, microwave heating, and oven heating the microwave-inactivated and -dried teas showed the highest levels of total phenols and catechins, and their infusions were bright in color and sweet in taste with a subtle, pleasant odor (Gulati et al., 2003).

Microwave processing can be also used as a method for reducing salmonella in peanut butter without producing quality deterioration (Song and Kang, 2016). Conventional thermal processes have been very reliable in offering safe sterilized meat products; however, flavor, aroma, and texture, among other attributes, are significantly affected during such processes (Barbosa-Cánovas et al., 2014) and microwave is one of the emerging, US food and drug administration (FDA)-approved technologies for avoiding these issues. When a commercially available inverter-based microwave oven was modified for the pasteurization of mechanically tenderized beef, and the beef was inoculated with approximately 5 log(10) *Escherichia coli O157:H7*, the complete inactivation of *E. coli* and background microflora was observed with heating at temperatures above 70°C for more than 1 min (Huang and Sites, 2010).

Microwave was also efficient in eliminating food-borne pathogens on catfish fillet surfaces. When a microwave with feedback power control was applied to inactivate cocktails of *Listeria monocytogenes, E. coli O157:H7*, and *Salmonella spp*., which were inoculated onto catfish fillets greater than 4 to 5 log colony-forming units, reductions were achieved within 2 min of 1250 W microwave heating (Sheen et al., 2012). On the other hand, microwave may also be a tool for the treatment of kitchen waste (Katschnig, 1991).

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Among other technologies, microwaves also have potential to be utilized for drying biotherapeutic products as an alternative to commonly used freeze-drying (Walters et al., 2014). Regarding therapeutic products, microwave freeze–thaw treatment of injectable drugs can support the development of centralized intravenous admixtures services (Hecq et al., 2012). An application of microwaves for vaccine production was suggested (Craciun et al., 2009) but was not yet converted into a commercial success.

For fragrance production, microwave-assisted techniques have been introduced as a viable alternative for the isolation of essential oils from herbs, flowers, and spices. They have shorter extraction times and provide a higher quality essential oil with better sensory and antioxidant properties (Kokolakis and Golfinopoulos, 2013). Microwave-assisted extraction also became one of the most popular and cost-effective extraction methods for natural products and of active ingredients from plants (Chan et al., 2011; Delazar et al., 2012).

Another potential application of microwaves could be the preparation of safe drinking water. When modified carbon nanotubes with 1-octadecanol groups (C_{18}) were combined with microwave irradiation, a removal of *E. coli* bacteria in water of up to 100% was achieved in contrast to a low removal rate of 3–5% for nanotubes alone (Al-Hakami et al., 2013).

These examples show that microwave technology nowadays has gained attention from researchers in a wide spectrum of applications and is not only used for cooking at home. Even in the home environment microwave radiation may be a reasonable tool for microbial inactivation. Kitchen sponges, scrubbing pads, and syringes were experimentally contaminated with wastewater and subsequently exposed to microwave radiation. At 100% power level, it was found that the total bacterial count was reduced by more than 99% within 1–2 min, and, depending on the organism, complete inactivation was achieved over longer exposures (Park et al., 2006).

Microwaves also hold great potential as one of the emerging technologies to treat biohazardous waste, including material from healthcare facilities. Microwave technology may be especially helpful in solving specific issues with waste in developing countries (de Titto et al., 2012).

When screening the peer-reviewed literature the reality is that only limited information is found in this area of work and, furthermore, analysis of the references reveals that sometimes not all necessary aspects for the appropriate use of the technology are considered.

Methodology

The main focus of this mini-review was to assess the use of microwave technology for the treatment of (solid) biohazardous waste. In order to get an initial overall insight into microwave technology, peer-reviewed literature in PubMed available up to spring 2016 was first screened by combining the keywords "microwave" and "review". This search led to 1741 articles; however, only a very limited amount could be associated with the treatment of biohazardous waste and none of these articles compared the differences between conventional and sophisticated microwave technologies. In the next approach the literature was analyzed by combining the terms "microwave" and "inactivation" or "waste", resulting into 642 articles.

Due to the relatively low number of articles written in the field, the search was improved by screening reports and other public documents published by international organizations; documents from the World Health Organization (WHO) and the United Nations Environment Programme (UNEP) were especially helpful. Also, suppliers of microwave devices were asked whether they were aware of further peer-reviewed literature. And finally, legislation and policy documents, from the German Robert Koch Institut for example, were taken into account.

Results and discussion

Biohazardous healthcare waste

The typical composition of healthcare waste is approximately (i) 85% general/non-infectious; (ii) 10% infectious/hazardous; and (iii) 5% chemical/radioactive (UNEP, 2012; WHO, 2014). Segregation of waste is an important factor to save costs, especially in low-income countries, and the disposal of untreated contaminated material on the ground, such as dump sites, landfill, and pits, should be avoided. Also, ecological aspects such as the segregation of waste (which could allow for partial recycling) prior to inactivation should not be neglected. Training of personnel is an important measure to encounter these issues. When a new low-cost, state-of-the-art healthcare waste management system was implemented in all rural hospitals in Kyrgyzstan, which included mechanical needle removers, segregation using autoclavable containers, safe transport and storage, autoclave treatment, documentation, recycling of sterilized plastic and metal parts, cement pits for anatomical waste, composting of garden wastes, training, equipment maintenance, and management by safety and quality committees, this process showed an average 33% annual cost savings (Toktobaev et al., 2015).

The inappropriate treatment and final disposal of wastes containing biohazardous materials which are produced in healthcare and other facilities working with pathogens buries especially in developing countries a variety of issues potentially leading to adverse impacts to public and occupational health and safety, as well as to the environment (Diaz et al., 2005). Healthcare waste must thus be carefully managed in accordance to the relevant regulations.

Significant global differences exist in the management of healthcare waste, especially between low-, middle-, and high-income countries (Caniato et al., 2015). When health care waste (HCW) disposal practices in a hospital in El Salvador were studied by observing waste containers and re-segregating waste placed in biohazardous waste bags, it showed that 61% of this waste was common waste, suggesting that the staff were possibly unaware of the cost of mis-segregating healthcare waste (Johnson et al., 2013).

The analysis of waste management practices in three government hospitals of Agra, India indicated lack of knowledge and awareness regarding legislations on bio-medical waste management, even among qualified hospital personnel (Sharma and Chauhan, 2008). Furthermore, none of these hospitals were equipped with higher technological treatment options and had no facilities to inactivate liquid waste. Other examples of potential mismanagement are the studies of Nandwani (2010) and Zhang et al. (2013).

However, the situation for developed countries is also far from perfect. In a large survey of private outpatient healthcare facilities in Europe, it was found that compliance with the law is far from ideal, and education and training is the strongest policy factor influencing the degree of compliance (Botelho, 2012).

There are four basic processes for the treatment of biohazardous components in healthcare waste: thermal (e.g. incineration, autoclave, microwave), chemical, irradiative, and biological. Thus, the use of microwave technology has to always be seen in the context of other treatment options. Each treatment technology has its pros and cons, and one of them may not be optimal for every need. A first guideline for accepted treatment options and processes can be found, for example, in the list of the German Robert Koch Institut (RKI, 2013).

A systematic approach is necessary to analyze whether microwaves have a potential for improving the management and treatment of biohazardous waste in comparison to other technologies.

Inactivation of pathogens by microwave devices

The ability to destroy pathogens should be without doubt the key factor for evaluating treatment technologies for healthcare waste. The destruction of all microbial life, termed sterilization, is usually not required by law for the inactivation of healthcare waste (see, e.g., VROM, 2006), whereas disinfection, which is the reduction or removal of disease-causing microorganisms in order to prevent any potential for transmission, is regarded as sufficient.

Regarding the ability to destroy pathogens, there is now convincing evidence that specially constructed microwave systems are able to sufficiently inactivate microorganisms.

In microwave systems, disinfection occurs through the action of moisture and low heat. Microwave units usually operate at a frequency of 2450 MHz and the energy generates hot water and steam.

Already in the 1960s, suspensions of *E. coli* and *Bacillus subtilis* spores were exposed to conventional thermal energy and, in comparison, to microwave at 2450 MHz. An approximately 6-log-cycle reduction in viability was encountered for *E. coli*. Reduction by heating of *B. subtilis* spores with conventional and microwave energy was also identical. It was stated that the inactivation of *E. coli* and *B. subtilis* by exposure to microwaves was solely due to the thermal energy (Goldblith and Wang, 1967).

In another study, *E. coli* cells were suspended in a solution and the kinetics of destruction were analyzed using a microwave oven. The number of viable cells decreased according to the exposure time and the power (Fujikawa et al., 1992).

For healthcare waste, scientists at the National Institute of Standards have devised a way to sterilize medical instruments and waste for hospitals in a device similar to a conventional microwave oven and termed this the "sterilization wave of the future" (Souhrada, 1989).

Within a full load of clinical waste, bacterial and thermometric test pieces were passed through a microwave system with a self-generated steam decontamination cycle (Hoffman and Hanley, 1994). These test pieces were enclosed in aluminum foil to shield them from direct microwave energy. After the treatment, none of the 100 bacterial test pieces yielded growth on culture and all pieces achieved temperatures in excess of 99°C during their passage through the decontamination unit. Moreover, no particles were detected outside the machine.

In a further study, a microwave unit was shown to provide multiple logarithm reductions in both vegetative bacterial cell counts and bacterial spore counts in laboratory-inoculated samples of turkey carcasses (Devine et al., 2007). The experiment was designed to simulate a poultry mass mortality event and generated a 7-log reduction in the microbial load of *Salmonella enterica* and a 5-log reduction in *Bacillus atrophaeus* spores.

Clearly, the operational conditions have to be strictly controlled. In one study, public healthcare wastes which had been pre-sterilized in an autoclave were inoculated with 5×10^5 vegetative *E. coli* bacteria and processed on laboratory scale in a microwave (Tonuci et al., 2008). Radiation exposure time and power per waste mass unit on the percentage of inactivation of the microorganisms at an incoming waste moisture level of 50% was analyzed. The results led to the conclusion that the operational conditions of the equipment currently used in Ribeirão Preto, Brazil are probably ineffective. Another study with similar results was conducted with spores of *B. atrophaeus* for microwave processing on a laboratory scale (Oliveira et al., 2010). In addition to the thermal effect on the inactivation of these spores, an undetermined effect inherent to radiation was suspected. Microwave showed also to be a simple and time-efficient tool to inactivate *Clostridium difficile* spores (Ojha et al., 2015).

When solid waste landfill leachate and sewage sludge samples were inactivated with different technologies and tested for viable *Enterocytozoon bieneusi, Encephalitozoon intestinalis, Encephalitozoon hellem*, and *Encephalitozoon cuniculi* spores, microwave was 100% ineffective against the spores of *E. bieneusi* and *E. intestinalis* (Graczyk et al., 2007). On the other hand, the effective disintegration of gram-negative cell walls in municipal secondary sludge by microwave was confirmed by scanning electron microscopy and it was suggested that this technology could be an effective pretreatment method for sludge that is dominated by gram-negative microorganisms (Zhou et al., 2010).

When a range of ultrasonication and microwave sludge pretreatments were compared to determine the extent of cellular destruction in microorganisms within secondary sludge, the microwave pretreatment of thickened waste-activated sludge caused fourfold to fivefold greater cell death than ultrasonication. However, when subsequently fed to anaerobic digesters, the improvements of microwave pretreated sludge were relatively small (Cella et al., 2016). Other positive effects for the treatment of sludge were also observed (Hong et al., 2006; Pino-Jelcic et al., 2006). These studies show that microwave technologies may have some potential for certain applications in sludge treatment, but not as a general tool.

Interestingly, when the microbicidal mechanisms of high-power microwave irradiation on *B. subtilis* were investigated transmission electron microscopy images showed that the cytoplasmic protein aggregation and cell envelope damage by microwave irradiation were different from the ultrastructural changes observed after boiling (Kim et al., 2008). The same author also investigated the sporicidal mechanisms of microwave irradiation on *Bacillus licheniformis* spores and found that 2.0 kW irradiation ruptures the spore coat and inner membrane, but different from boiling (Kim et al., 2009).

The ionic strength of solutions also has some influence on the inactivation of microorganisms by microwave irradiation (Watanabe et al., 2000).

The cited studies make it clear that microwave technology is a useful tool for the inactivation of pathogens occurring in biohazardous waste, including healthcare waste; however, the process has to be strictly controlled by special microwave devices. One wide misbelief is that microwave systems cannot be used for inactivation because a solid waste cannot be treated efficiently. This is not even true for conventional microwave ovens available on the market, which may be used for a high level of disinfection as long as sufficient water is present (Najdovski et al., 1991). However, conventional microwave units have no means to control the inactivation process, and especially the moisture content.

But there are a few sophisticated microwave technologies with appropriate measurements not only described in the literature but also commercially available. While these technologies are currently only used for the treatment of biohazardous waste, it still needs to be evaluated whether they would also have advantages for processes involving the control of water content such as the drying of biotherapeutic products (Walters et al., 2014) or the isolation of oils from herbs, flowers, and spices (Kokolakis and Golfinopoulos, 2013.

Sophisticated microwave technologies

In principal, there are two system designs: batch processes and semicontinuous microwave systems (WHO, 2014). When evaluating different microwave treatment technologies and/or comparing them with other treatment technologies, it is essential to consider this difference.

The Sanitec waste disposal system is based on continuous microwave technology, including a shredding system and air filters (Edlich et al., 2006). The first Sanitec system was installed at Forsyth Memorial Hospital, Winston-Salem, NC, USA in 1990 (Brewer, 1993). As a result, 90% of the hospital's infectious waste could be sent to the local landfill. It should be noted that the Sanitec system is intended for large hospitals and service providers for the treatment of large amounts of biomedical waste.

The AMB Ecosteryl Microwave's continuous disinfection system also combines internal shredding and microwave energy to heat healthcare waste to about 100°C. For example, the AMB Ecosteryl Serial 250 allows to handle 250 to 300 kg/hour. The shredded waste, which is reduced to less than 20 mm pieces, is held at the disinfection temperature for one hour. The residue is a dry shredded waste reduced by 80% in volume. As the capacity is 800 kg per hour or more, large hospitals as well as service providers are also customers for this system.

The disadvantage of these large and invariably centralized disinfection systems is that the waste is not inactivated directly at the place where it is generated, but rather collected throughout the whole hospital, transported, and then inactivated at one single site. If no properly controlled means for transport between the different locations are installed this procedure always bears the risk of contamination of the environment or humans. A repair of the shredder system also bears contamination risks of the service personnel and the system should, thus, also provide the means to disinfect the shredder before maintenance or repair. Furthermore, the huge capacity of these systems might influence the decision whether waste should be segregated or not. If the waste is not segregated at all, approximately 90% of the waste would be treated unnecessarily.

In respect of biosafety guidelines, the transport of inactivated material outside the place of generation should be at least avoided (biosafety level 2) or is forbidden (biosafety level 3 and 4), respectively. According to national legislations, healthcare facilities are often exempted from these guidelines and it is within the responsibility of the hospital management to make the best out of it (WHO, 2014). As an example, in the Netherlands hospitals are not allowed to discard hospital waste as normal industrial waste and it suggested that a hospital may choose, "for aesthetic reasons", to decontaminate hospital waste before transporting it to a regional waste incinerator (VROM, 2006).

Smaller amounts of infectious waste which have been previously shredded and moisture-corrected can be treated by a microwave technology operating at 2.45 GHz, a power of 3 kW, and 7 atm (Veronesi et al., 2007). Sterilization was achieved in just a few minutes for a batch of several hundred grams of waste. Sterilization efficacy was further optimized by using thermal, microbiological, and water vapor sensors. This device, however, was never developed into a commercial product.

Another company offering sophisticated microwave technologies for smaller amounts of waste is Bertin; its technology is also using a shredder/microwave combination.

Table 1. Advantages/disadvantages of conventional and sophisticated microwave technologies.

	Conventional microwave	Sophisticated microwave	Autoclave
Cost of device	Low	High	High
Energy consumption	Low	Low	High
Water consumption	None	Low	High
Control of inactivation process	Difficult	Very good	Very good

The Meteka batch microwave technology guarantees a controlled even heating of waste, including inhomogeneous compositions of material (Colgate, 2000; Dragas et al., 1994; Katschnig, 1993; Mucha, 2001). The environmental performance of this system is communicated through Environmental Product Declarations according to the principles of ISO 14025:2006. The heat/steam is generated directly in the moisture waste. In addition, the system offers a closed waste collection system in which the material is directly inactivated. Different waste container volumes are available and, when full, it is closed, wheeled to the microwave unit, and detached from the pedal-operated stand. The microwave device automatically adds water and controls moisture air, heats up the waste, and maintains the waste at the pre-set temperature for 25 min with material-adapted disinfection cycles before cooling down and allowing the waste to be removed. This technology is especially appropriate for settings where the waste has to be inactivated at the site where it is generated. Table 1 gives a short summary of the major advantages and disadvantages of conventional and sophisticated microwave technologies in comparison to autoclaves, as discussed in the previous sections.

Life cycle assessment of environmental impacts

In general, there are hardly any peer-reviewed references available which address the issue of the environmental impacts of microwave technology, especially in comparison to standard technologies. Similarly, McGain and Naylor, (2014), who analyzed environmental sustainability in hospitals, concluded in their systematic review by using search terms such as direct energy consumption and waste, among others, that there remain significant gaps in the assessments of environmental impacts.

Usually, environmental impacts are analyzed in a life cycle assessment (LCA). Liamsanguan and Gheewala, (2008) applied a LCA to municipal solid waste management systems to identify the overall environmental burdens and to assess the potential environmental impacts for a number of different technologies.

Wittmaier et al. (2009) assessed emissions from different options for thermal treatment and energy recovery from waste in a region in Northern Germany using the LCA approach, and De Feo and Malvano, (2009) focused in their LCA on incineration, final landfilling, and recycling issues.

Soares et al. (2013) performed a thorough LCA and cost analysis for microwave, autoclave, and lime disinfection technologies and also assessed their environmental impact (see also section below). Moreover, a comprehensive overview analyzing a variety of factors relevant for environmental impacts and also considering national and international reports of organizations responsible for waste management is compiled in the "UNEP compendium of technologies for treatment/destruction of healthcare waste" (UNEP, 2012). Table 2 gives an indicative summary of the environmental aspects discussed in the respective chapter of the compendium. A further overview for this topic can be found in the "Guidelines on best available techniques and provisional guidance on best environmental practices relevant to Article 5 and Annex C of the Stockholm Convention on Persistent Organic Pollutants" (UNEP, 2006).

Table 2. Summary of the environmental aspects of treatment technologies (adapted from UNEP, 2012).

Technology	Air	Water	Solid residue
Autoclaves	x	xx	x
Batch microwave	x	x	x
Continuous microwave	x	x	x
Frictional heat	x	x	x
Dry heat treatment	x	x	x
Incinerators	xxx	xx*	xxx
Alkaline hydrolysis	x	xxx	x
Chemical	xx	xx	x

x: minimal concerns; xx: some concerns; xxx: significant concerns.
*Treatment of the incinerator's flue gas cleaning wastewater.

It should be noted, however, that facilities working with biohazardous waste should not only take into regard environmental impacts alone, but also identify closely related occupational hazards arising from the handling, treatment, and disposal of medical waste. Moreover, institutional and regulatory requirements and policies for treatment technologies may strongly influence environmental factors (UNEP, 2012). On the other hand, these requirements may be ineffective or even non-existent in developing countries (Nandwani, 2010; Sharma and Chauhan, 2008; Zhang et al., 2013).

Comparison of microwave to other waste treatment technologies

For objectively comparing the pros and cons of the basically different waste treatment technologies, there are only a few examples in the literature. Diaz et al. (2005) gave some background information on technologies such as autoclave, microwave, chemical disinfection, combustion (low-, medium-, and high-technology), and disposal on the ground (dump site, controlled landfill, pits, and sanitary landfill). An alternative for treatment and disposal was also explained, including a description of the types of wastes that can be treated.

In China, from 272 modern, high-standard, centralized medical waste disposal facilities operating in various cities there were about 50% non-incineration treatment facilities, including the technologies of high temperature steam, chemical disinfection, and microwave (Chen et al., 2013). For the application in China, each of the non-incineration technologies has its advantages and disadvantages; for example, the non-incineration treatment of medical waste would avoid the release of polychlorinated dibenzo-p-dioxins/dibenzofurans.

For regulated medical wastes obtained from three city hospitals in Massachusetts, the generation volume and sources, composition, treatment, and disposal methods, as well as the generation patterns and amounts between the hospital and the medical school, were investigated. The most cost-effective option of four different treatment and disposal options studied was to combine on-site incineration and microwave technologies (Lee et al., 2004).

The amount of (non-separated) healthcare waste produced in the Istanbul Metropolitan City in Turkey is 30 ton per day in total. Alternatives for the treatment and disposal of this huge amount of waste were evaluated, including incineration, microwave irradiation, and mobile or stationary sterilization. The capital investment cost and transportation/operational costs for each alternative method and the different locations for installation were compared. It was concluded that the method for the final disposal of most of the healthcare waste of Istanbul is and should remain incineration (Alagöz and Kocasoy, 2007).

However, this conclusion is still controversial. In another study in Turkey, the most appropriate treatment/disposal option was investigated by using two multi-criteria decision-making techniques (Özkan, 2013). Five different healthcare waste treatment/disposal alternatives, including incineration, microwaving, on-site sterilization (autoclaving), off-site sterilization (autoclaving), and landfill, were evaluated. According to the comparisons, the off-site sterilization technique (i.e. autoclaving) was found to be the most appropriate solution for the specific requirements.

These studies imply that it is still necessary to decide case by case how to best meet local biohazardous waste management needs while minimizing the impact on the environment and public health, and that there is an obvious need for objective factors for evaluation. Direct comparison between the references is also complicated due to the fact that the use of on-site units or central plants, as well as batch or semicontinuous systems, may result in different ratings.

Regarding the fact that sophisticated microwave technologies are appropriate for the proven inactivation of biohazardous waste, another important factor for the evaluation of technologies is costs – including labor, energy, water, sewage, and, finally, landfill disposal. Also, consumables such as personal protection equipment and disposable boxes should be regarded. Furthermore, an important cost factor is also maintenance and repair (including replacement parts), which is relatively low for microwaves as compared to autoclaves.

The move away from landfill disposal of clinical wastes, and the development of high-temperature incinerators, has inevitably increased the cost of waste disposal and, in contrast, the development of newer waste treatments, including microwave exposure of macerated wastes, may reduce costs and aid in the control of environmental pollution (Blenkharn, 1995).

A systematic approach for analyzing all factors including costs can be found in the UNEP compendium of technologies for the treatment/destruction of healthcare waste (UNEP, 2012). Whereas the document gives no recommendation for any of the technologies, it shows how scores can be calculated from all aspects of environmental and occupational safety, operation costs, and technical comparison such as capacities, volume reduction, efficacy of inactivation, and installation requirements. Each potential user can objectively calculate which technology would be optimal for his needs.

A systematic costing approach includes additional costs such as administration, periodic training, regulatory fees, and employee benefits. Various aspects related to costs were assessed primarily by referring to vendor information, technology fact sheets, and expert opinions. Concerning operating costs, the compendium noted for autoclaves between US$0.14 and US$0.33 per kg and, for batch microwaves, about US$0.13 per kg, respectively (UNEP, 2012). These costs are only an average and not directly comparable, because they are also dependent on the range of capacities in a certain time frame.

As the assessment of healthcare waste disposal alternatives is a complicated multi-criteria decision-making problem which requires the consideration of multiple alternative solutions and conflicting tangible and intangible criteria, one possibility for evaluation is to use a technique based on fuzzy set theory and the VIKOR method (Liu et al., 2013).

Soares et al. (2013) also took a systematic approach for analyzing the costs of small generators of healthcare waste for three disinfection techniques (microwave, autoclave, and lime) followed by transportation and landfilling. The techniques were first tested by the authors to ensure their efficiency in disinfection. The technique with the best environmental performance was determined using a LCA by evaluating the eco-efficiency of each scenario. Microwaving had the lowest environmental impact (12.64 Pt) followed by autoclaving (48.46 Pt). The cost analyses indicated values of US$0.12 per kg for the waste treated with microwaves, US$1.10 per kg for the autoclave, and US$1.53 per kg for lime, respectively. The microwave disinfection thus presented the best eco-efficiency performance.

This study provided a high-level analysis of cost factors for the treatment of healthcare waste. However, there is a drawback in the work of Soares. An ordinary LG microwave was used for the inactivation experiments. Such equipment is relatively cheap in comparison to an autoclave, but lacks options for controlling the efficacy (heat and moisture). The authors conducted their own inactivation experiments for the study and the results were at least sufficient for their experimental set-up. But this scenario cannot be compared to waste normally generated in hospitals or other institutions working with biohazardous materials. These types of waste consist of a variety of different types of material and may, under certain circumstances, not contain enough moisture for efficient inactivation. It is surprising that up-to-date conventional microwave devices are used for the inactivation of biohazardous waste.

When various bacteria, actinomycetes, fungi, and bacteriophages were exposed to microwaves of 2450 +/– 20 MHz in the presence and in the absence of water, microorganisms were inactivated only sufficiently in the presence of water, and dry or lyophilized organisms were not affected even by extended exposures (Vela and Wu, 1979).

But as it is of utmost importance to control the inactivation process, "normal" microwave units should not be used for these materials. On the other hand, sophisticated microwave systems have prices starting at about US$20,000 for smaller units, which are comparable to prices of autoclaves with similar treatment volumes (UNEP, 2012). In respect of the huge amount of different autoclaves with enormous price ranges, it is thus difficult to take the purchase costs of the systems into fair calculation. If we omit the purchase costs of the various systems, then the calculation of costs can only be performed on the basis of energy costs, and additional costs such as maintenance.

When considering the scenario of a facility generating, for example, 150 kg of a typical mixture of solid biohazardous waste (the following calculations may vary slightly if the waste has an unusual composition) per day, an appropriate typical microwave unit for treatment would be, for example, a Medister 160. This system has 6.5 kW power input and treats containers of 60 L volume. Inactivation of 150 kg per day of typical waste needs approximately 12 runs with such containers. Total weight accumulates to 54.75 tons per year, assuming that the device is operated every day. The energy consumption for one run is 3.3 kWh (1 run = 45 minutes) and results in approximately 40 kWh/day. Standby energy consumption is 0.9 kWh/day, leading to an overall energy consumption of 40.9 kWh/day.

A typical comparable autoclave with 110 L chamber volume has 17 kW power input and approximately 10 runs consume 120 kwh/day (1 run = 70 minutes). Standby energy consumption is 22.4 kWh/day, leading to an overall energy consumption of 142.4 kWh/day. Thus, the difference accumulates to 101.5 kWh/day and when assuming a price of €0.2 per kWh, the cost save is approximately €20 per day. This calculation does not take into account that other costs such as water consumption and repair/service would, without doubt, increase the difference of the two systems. Table 3 gives a summary of the calculations of the above-described scenario.

Another important aspect is the environmental/ecological factor. Taking solely the difference in energy consumption of 37,000 kWh yearly (if operation is on a daily basis) into account and calculating the reduction of CO_2, that is, the carbon footprint, by assuming 0.583 kg CO_2 (based on the average global emission factor for all energy sources for power generation; IEA, 2014) for one kWh, the reduction of carbon footprint is a surprisingly high 21.6 tons CO_2/year.

Table 3. Comparison of treatment costs of sophisticated microwave vs autoclave.

	Microwave	Autoclave
Assumed weight of waste/day	150 kg	
Accumulated weight of waste/year	54.75 tons	
Maximum of volume/run	60 L	80 L
Power input	6.5 kW	17 kW
Runs per day	12	10
Duration/run	45 min	70 min
Energy consumption/run	3.3 kWh	12 kWh
Energy consumption/day including standby	40.9 kWh	142.4 kWh
Assumed price/kWh	€0.2/kWh	
Energy costs/day	€8.16	€28.48
Energy costs/year	€2,978.4	€10,395.20

The shredding of waste after the inactivation of previously separated infectious material may be a further tool to reduce the volume of waste and may also contribute to a reduction of carbon footprint by reducing transport. However, because larger materials may melt and form compact masses in which contamination may still be enclosed, the hospital waste should not be shredded after autoclave treatment (VROM, 2006).

Conclusions

Microwave devices are an effective tool for the inactivation of biohazardous waste as long as sophisticated microwave technologies are utilized. To avoid the spreading of pathogenic microorganisms during transport, the waste should preferably be inactivated either directly at the place where it is generated or transported only in appropriate closed systems. Moreover, microwave is a possibility to save energy costs in comparison to the more widely used autoclave technologies, thus leading to a reduced carbon footprint. In this respect, segregation between contaminated and non-contaminated waste and the subsequent inactivation of contaminated parts helps to further reduce the carbon footprint. Sophisticated microwave technology might also bear advantages for microwave-assisted processes requiring the control of water content.

Declaration of conflicting interests

The author declares no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author received no financial support for the research, authorship, and/or publication of this article.

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