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Review

Microwave Technologies: An Emerging Tool for Inactivation of Biohazardous Material in Developing Countries

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Abstract: Inappropriate treatment and disposal of waste containing biohazardous materials occurs especially in developing countries and can lead to adverse effects on public and occupational health and safety, as well as on the environment. For the treatment of biohazardous waste, microwave irradiation is an emerging tool. It is a misbelief that microwave devices cannot be used for inactivation of solid biohazardous waste; however, the inactivation process, and especially the moisture content, has to be strictly controlled, particularly if water is required to be added to the process. Appropriate control allows also inactivation of waste containing inhomogeneous compositions of material with low fluid/moisture content. Where appropriate, especially where control of transport of waste cannot be guaranteed, the waste should be inactivated directly at the place of generation, preferably with a closed waste collection system. In waste containing sufficient moisture, there are direct useful applications, for example the treatment of sewage sludge or human feces. A number of examples of microwave applications with impacts for developing countries are presented in this review. In respect to energy costs and environmental aspects, microwave devices have clear advantages in comparison to autoclaves.

Keywords: microwave; inactivation; disinfection; biohazardous waste; healthcare waste; sludge; carbon footprint; developing countries

1. Introduction

In developing countries, a relatively low number of research facilities or commercial companies are working with microorganisms in higher biosafety level (BSL) containments, and thus a large part of biohazardous waste is generated in hospitals. Sewage sludge is also one potential source of biohazardous waste and its treatment has considerable interest for these countries [1].

Usually 5–90% of hospital waste is general waste (similar to household waste) and about 10% is classified as biohazardous [2,3]. Other types of dangerous wastes are toxic and radioactive. Segregation of waste prior to decontamination and/or disposal could be an important factor to save costs, which is especially relevant for low-income countries. The transport from waste generating facilities to the disposal site bears considerable risks [4], but in reality, also uncontrolled transport ways within facilities or hospitals from the site of generation to the treatment site should not be disregarded. The final disposal of untreated contaminated material on the ground should be avoided and may lead especially in developing countries to adverse impacts [5].

A variety of waste treatment technologies are available, and there is not one which is optimal for every need. Relevant factors for using a specific technology including environmental impacts are compiled in the "United Nations Environment Programme (UNEP) compendium of technologies for treatment/destruction of healthcare waste" [2], which gives an excellent introduction into this topic.

From a variety of different technologies to treat biohazardous waste, microwave irradiation is emerging and may especially be helpful to solve specific issues in developing countries [6]. However, in peer-reviewed literature, only limited information about these topics is available and sometimes not all necessary aspects for appropriate use of microwave technology are taken into account. In this review, the aforementioned aspects are highlighted in the context of whether microwave technologies could be an alternative tool for improving the management and treatment of biohazardous waste with a focus on developing countries.

2. Treatment Technologies and Challenges

There are four basic processes for the treatment of biohazardous components in waste (i.e., thermal, chemical, irradiative, and biological). From the thermal processes, incineration and autoclave treatment are most widely used; however, microwave irradiation is an emerging tool.

Inappropriate treatment and final disposal of wastes containing biohazardous materials 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 [5]. Accepted treatment options and processes are listed for example by the German Robert Koch Institute [7].

Not unexpectedly, there are differences in the management of healthcare waste especially between low, middle, and high-income countries [8]. When the content of waste containers was observed in a hospital in El Salvador, 61% of biohazardous waste was actually common waste, suggesting that the staff was possibly unaware of the requirements or just neglected them [9].

Waste management practices in three government hospitals of Agra, India indicated also a lack of knowledge and awareness regarding legislations on bio-medical waste management [10]. Other examples of suboptimal waste management practices are presented by Nandwani [11] and Zhang et al. [12].

Inappropriate transport is also a major challenge. Biosafety guidelines demand that transport of inactivated biohazardous material outside the facility is forbidden if not using specific precautions. Though healthcare facilities are usually exempted from these guidelines, the hospital management should nevertheless consider the risk [3]. In order to avoid infections of humans and environmental contamination, a disinfection system minimizing the risk should be used. A good example (for a microwave device) is a closed waste collection system with different container volumes in which the material is subsequently inactivated (Figure 1, with kind permission of Meteka, Judenburg, Austria). Such technology is especially useful for developing countries where appropriate control of transport of waste cannot be guaranteed.

In respect to microwave technologies, Tonuci et al. [13] showed that if the operational conditions of the equipment are not adequately controlled, the inactivation treatment is probably ineffective. Clearly, operational conditions are the most important factor and without tight control of parameters, especially moisture, a complete inactivation can never be guaranteed with microwave technologies.

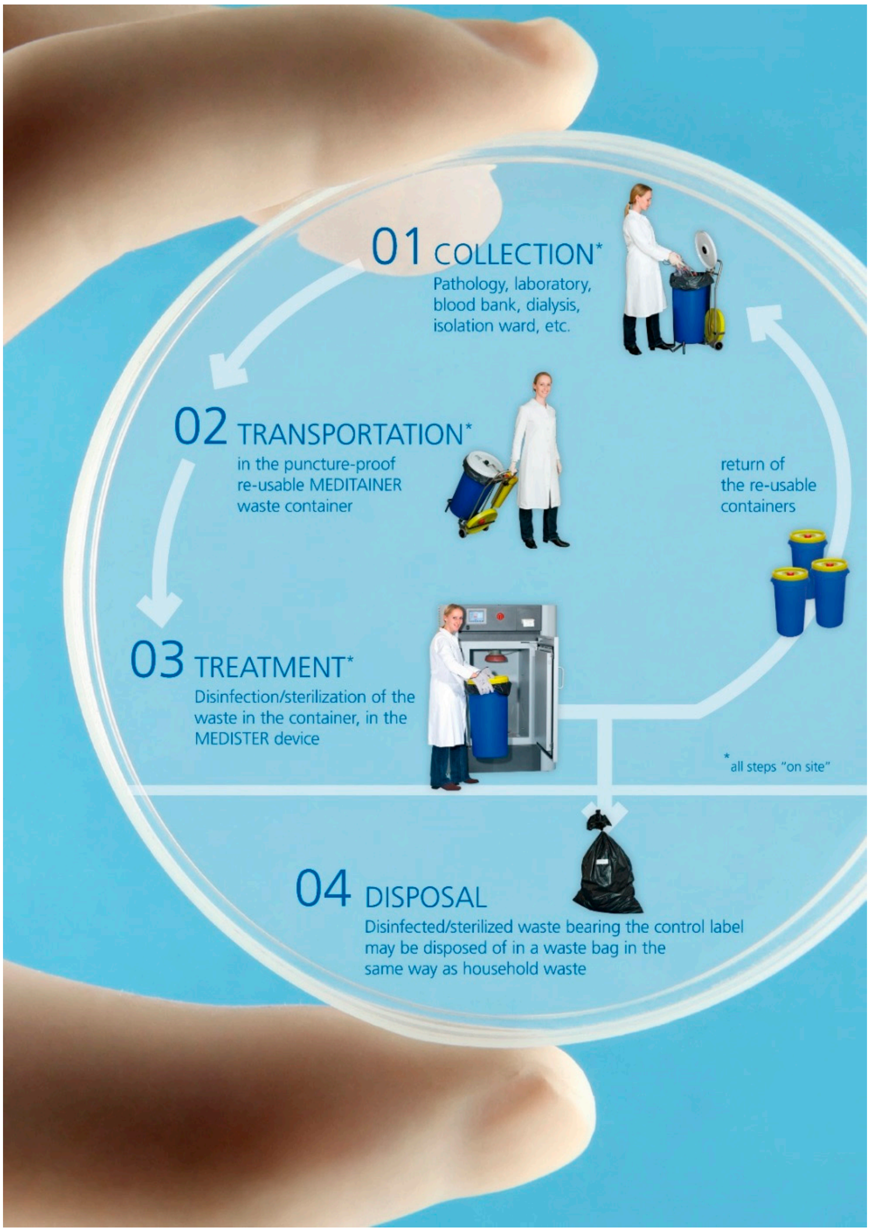

Figure 1. Example for closed waste disinfection system.

3. Microwave: A Variety of Applications

The main benefit of microwave energy is the direct delivery of energy to microwave-absorbing materials. As long as a material contains dipolar molecules (i.e., water), a complete heating of samples from outside and inside is guaranteed. Issues such as long heating periods, thermal gradients, and energy loss to the environment can thus be minimized [14]. Disinfection with microwave irradiation occurs mainly through the combination of moisture and (low) heat. In contrast to microwaves, the heat for autoclaves is generated outside of the waste material, and thus the material to be treated is heated starting from the surface [2]. Every type of material is inactivated; however, to be on the safe side, extended inactivation times should be used for waste with a large volume. A schematic drawing of the two principles is shown in Figure 2.

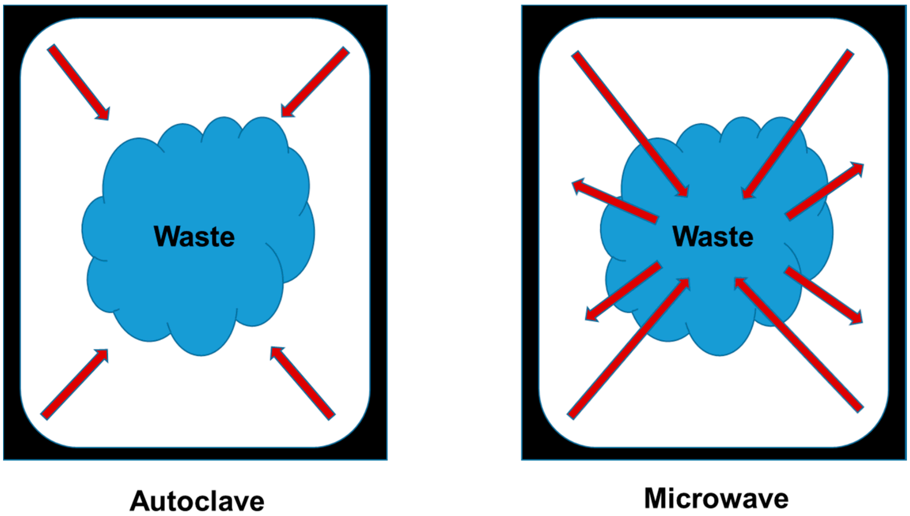

Figure 2. Heat generation in microwaves.

The majority knows microwave ovens just as a tool for cooking at home. It is not widely known, but even at home, microwave radiation can be used for microbial inactivation. When treating kitchen sponges, scrubbing pads, and syringes with microwaves at 100 percent power level, the total bacterial count can be reduced by more that 99 percent within 1 to 2 min, and complete inactivation can be achieved over longer exposures [15].

In recent years, microwave technologies proved to be a very attractive alternative for industrial conventional processing methods, and found an astonishing number of applications in different areas. In respect of processing food or beverages, one of its applications is drying of green tea [16]. However, main applications for food or beverages are inactivation of microorganisms, for example in or on peanut butter [17], beef [18], or catfish filet [19].

Regarding therapeutic products, microwaves are useful for freeze-thaw treatment of injectable drugs [20] or hold potential for vaccine production [21]. Microwave assisted extraction is a possibility for fragrance production [22], and became a popular method for extracting natural products and active ingredients from plants [23,24]. Another potential application of microwaves could be the preparation of safe drinking water [25].

4. Efficiency of Microwaves for Treating Biohazardous Waste

The destruction of all microbial life—sterilization—is usually not required for inactivation of healthcare waste [26], whereas disinfection—the prevention of any potential for transmission—is regarded as sufficient.

For many years, there seem to be no doubt that microwave systems are able to destroy pathogens. Already in the 1960s of the last century, suspensions of *E. coli* and *Bacillus subtilis* spores were exposed to a conventional microwave at 2450 MHz and approximately a 6-log cycle reduction in viability was encountered for both microorganisms [27]. Another early study supporting the efficient inactivation of microorganisms with "ordinary" microwaves was conducted by Souhrada [28]. Hoffman et al. [29] already used a more sophisticated microwave system with a self-generated steam decontamination cycle for inactivation of bacteria.

It became clear that the operational conditions have to be strictly controlled for microwave inactivation of microorganisms. Pre-sterilized public healthcare wastes, which were inoculated with 5×10^5 vegetative *E. coli* bacteria and then treated with a microwave device [13] showed that not only radiation exposure time and power per waste mass unit were important for the percentage of inactivation of the microorganisms, but also the incoming waste moisture had an significant influence.

If properly controlled, the misbelieving that microwave systems cannot be used for inactivation of solid biohazardous waste is thus contradicted. However, the inactivation process, and especially the moisture content has to be strictly controlled.

5. Advanced Microwave Technologies

In principal there are two system designs for advanced microwave technologies: batch processes and semi-continuous microwave systems [3]. The Sanitec waste disposal system is an example for continuous microwave technology including a shredding system [30]. This system is intended rather for the treatment of large amounts of biomedical waste, which inherently leads to collection of the waste at sites where it is generated, transport, and inactivation at one single site. For smaller amounts of waste, other microwave technologies combined with shredding are available as well [31]. Among the commercial suppliers is the company Bertin.

The Meteka batch microwave technology guarantees a controlled even heating of waste including also inhomogeneous compositions of material [32,33]. The environmental performance of this system is proven through environmental product declarations (EPDs). The microwave device automatically adds water and controls moisture air, and heats up and inactivates the waste. Table 1 gives a short summary of major advantages and disadvantages of conventional and sophisticated microwave technologies [34].

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

	Conventional ("Household") Microwave	Sophisticated Microwave (Controlled Heat and Moisture)
Cost for device	Low	High
Energy consumption	Low	Low
Water consumption	None	Low
Control of inactivation process	Difficult	Very good

6. Comparison of Technologies for Treatment of Biohazardous Waste

For decontamination of infectious waste autoclaves are widely used. However, these devices have the disadvantage that they have a high energy consumption and a long runtime per disinfection cycle. Due to the operating conditions—overpressure and high temperatures—autoclaves demand more technical handling, have a high service requirement, and a comparatively limited durability.

Another widely used option is disposal and/or incineration of special waste. However, this option requires transport, mainly on the road. The transport risks are directly related to the operation safety of the dangerous goods transport enterprises and can be mathematically calculated [4]. The validity of the calculation was proven in a case analysis of five dangerous goods transport enterprises in the Inner Mongolia Autonomous Region.

The pros and cons of different waste treatment technologies must thus be objectively analyzed. An analysis on technologies such as autoclave, microwave, chemical disinfection, combustion, and disposal on the ground was carried out by Diaz et al. [5]. One large study comparing technologies was also conducted in China. From 272 modern, high-standard, centralized medical waste disposal facilities there were about 50% non-incineration treatment facilities, including the technologies of high temperature steam, chemical disinfection, and microwave [35], and every technology was found to have its advantages and disadvantages.

In a study in Istanbul, Turkey, it was concluded that the method of choice for the healthcare waste for this city would be incineration [36]. However, another study in the same country led to different results. When five different healthcare waste treatment/disposal alternatives including incineration, microwaving, autoclaving on-site, autoclaving off-site, and landfill were evaluated, the off-site autoclaving was found to be the most appropriate solution for the specific requirements [37].

A systematic approach for analyzing all factors including costs can be found in the UNEP compendium of technologies for treatment/destruction of healthcare waste [2]. The UNEP compendium advises to calculate scores from all aspects of environmental and occupational safety, operation costs, capacities, volume reduction, efficacy of inactivation, and installation requirements. In this study, costs stated for autoclaves were calculated to be between 0.14 and 0.33 USD/kg and for batch microwaves about 0.13 USD/kg.

Depending on the type of analysis, cost calculations do not always deliver the same result. Soares et al. [38] conducted a systematic approach for analyzing costs of small generators of healthcare waste for three disinfection techniques (microwave, autoclave, and lime) followed by transportation and landfilling using a life-cycle assessment. Microwaving had the lowest environmental impact (12.64 Pt) followed by autoclaving (48.46 Pt). Cost analyses revealed values of USD 0.12/kg for microwaves and USD 1.10/kg autoclaves. The conclusion was that microwave disinfection had the best eco-efficiency performance. It has to be noted that an ordinary household microwave was used for the inactivation experiments. As these microwave instruments are relatively cheap, but lack options for controlling the efficacy (heat and moisture), the costs need a recalculation in case advanced microwave technologies would be applied (prices starting at about USD 20,000 for smaller units).

With regard to the many differences in technologies and features of commercially available devices, a fair price comparison is hardly possible. Clearly, a comparison of costs of microwaves and autoclaves cannot simply be reduced to the price of the device. However, in respect of energy costs and additional costs such as maintenance there is a clear difference. An example was calculated for 150 kg of a typical mixture of solid biohazardous waste per day using a Medister 160 microwave device with 6.5 kW power input [34]. Inactivation of 150 kg waste needs approximately 12 runs with 60 L containers. The overall energy consumption is 40.9 kWh/day. In comparison, a typical autoclave with 110 L chamber volume and 17 kW power input has an overall energy consumption of 142.4 kWh/day. With a price example of 0.2 €/kWh, the cost save accumulates to an astonishing 20 €/day. In addition, the environmental factor should not be neglected. Based on a daily operation, the difference in energy consumption would be 37,000 kWh yearly. Assuming 0.583 kg CO_2 (International Energy Agency 2014) for one kWh the reduction of carbon foot print is 21.6 tons CO_2/year.

7. Examples for Use of Microwaves in Developing Countries

Microwaves hold great potential to treat biohazardous waste and may especially be helpful to solve specific issues with waste in developing countries [6]. Challenges and consequences of poor sanitation, especially in developing economies, demand the exploration of new sustainable sanitation technologies [1]. The treatment of sewage sludge is one of the widely discussed applications.

7.1. Sewage Sludge

The treatment of sewage sludge is a widely discussed application of microwave technologies and has generated considerable interest in developing countries. Sewage is an organic-rich resource that is typically high in moisture (up to 97%), making it a suitable candidate for microwave irradiation [1], without needing advanced technologies.

Not all studies opt for microwave technologies. When solid waste landfill leachate and sewage sludge samples were inactivated with different technologies and tested for several spores, microwaving was ineffective against the spores of *E. bieneusi* and *E. intestinalis* [39]. In addition, when a range of ultrasonication and microwave pretreatments in thickened sewage sludges were examined, the improvements for microwave pretreated sludge were relatively small [40].

In contrast to these studies, effective inactivation of Gram-negative microorganisms was achieved by microwaves in municipal secondary sludge [41]. Other positive effects for the treatment of sludge were observed as well [42,43]. When microwave treatment of fecal sludge from toilets in the slums of Nairobi, Kenya was studied [44], it was demonstrated that the microwave technology efficiently inactivated *E. coli* and *Ascaris lumbricoides* eggs, and it was concluded that the technology can be applied under real field conditions.

Similarly, treatment of human feces with microwave radiation showed efficient pathogen eradiation performances of six log units or more within a high range of microwave powers. In addition, enhanced moisture removal and volume reduction was achieved. The product was suggested to be used also as compost [45]. Microwaving human fecal sludge represents a thermally effective approach that not only destroys pathogens, but also eradicates the foul odor associated with human fecal sludge, improves de-waterability and heavy metals recovery, and reduces emissions [1].

Microwave pretreatment also significantly improved the dehydration and hydrogen production of sludge subjected to anaerobic digestion [46]. Furthermore, this study may provide theoretical and experimental basis for the development of a continuous microwave sludge-conditioning system. Microwave-H_2O_2 pretreatment on concentrated sludge anaerobic digestion showed in a study in China that a mixture of activated sludge and pretreated sludge at mass ratio of 1:1 was efficient for enhancing anaerobic digestion and methane production [47]. In a study in India, microwave irradiation has been used to disintegrate sludge biomass by de-agglomerating it with an ultra-sonicator and a net profit of 2.67 USD/t was calculated for this procedure [48].

Microwaves in combination with other methods hold also potential for the reduction of antibiotic resistant bacteria and antibiotic resistance genes during sludge treatment [49].

7.2. Healthcare Waste

The most widely used application of microwave irradiation is in the field of healthcare waste. Unfortunately, most economically developing countries suffer a variety of constraints to adequately manage healthcare wastes. Usually, only a few individuals in the staff of a healthcare facility are familiar with a proper waste management program [5]. How to perform an assessment of healthcare waste disposal alternatives including microwaves was illustrated for example with a case study in Shanghai [50]. It has to be decided case by case how to best meet the local biohazardous waste management requirements while minimizing the impact on the environment and public health.

Not unexpectedly, a major constraint is equipment itself. For example, when waste management practices in three government hospitals in Agra, India were studied, it was revealed that none of these hospitals were equipped with higher technological options such as incinerator, autoclave, and microwave. Furthermore, facilities to treat liquid waste generated inside the hospital [10] were not available.

There are number of successful practical uses of microwave technologies in developing countries. When studying 272 modern, high standard, centralized medical waste disposal facilities operating in various cities in China, the application of non-incineration technologies including microwaves was recommended [35]. Soares et al. [38] pointed at two different profiles of waste generators: (i) hospitals, which produce large quantities of healthcare waste; and (ii) small establishments, such as clinics, pharmacies, and other sources that generate dispersed quantities of healthcare waste and are scattered throughout the city. The microwave disinfection presented the best eco-efficiency performance of several studied technologies for small generators of healthcare waste. In Thailand, the influence of microwave irradiation in addition to conductive heating was studied for inactivation of 15 different *C. difficile* spores in aqueous suspension, and microwave proved as a simple and time-efficient tool to inactivate the spores [51].

Oliveira et al. [52] inoculated pre-sterilized public healthcare wastes from the region of Ribeirão Preto, Brazil with spores of *Bacillus atrophaeus* and inactivated the samples with microwave irradiation. The influence of waste moisture, presence of surfactant, power per unit mass of waste, and radiation exposure time was investigated. Microwave irradiation was successful and optimal conditions for inactivation of the *B. atrophaeus* spores in typical healthcare waste were demonstrated. Previously, in a similar study in Ribeirão Preto, *Escherichia coli* in vegetative form were processed in microwaves [13]. Under the operational conditions of the equipment employed in this study, the process of inactivation was ineffective, because the exposure time to radiation average power of approximately was probably inadequate—again pointing to control the inactivation conditions.

Further future potential applications of microwave technologies with impact for developing countries could be in the destruction of dioxins in the froth product after flotation of hospital solid waste incinerator fly ash [53].

8. Conclusions

Microwave irradiation is without doubt an effective tool for inactivation of solid biohazardous waste. However, the inactivation process, and especially the moisture content is not always strictly controlled. In the future only sophisticated microwave technologies allowing appropriate control of heat and fluid/moisture content should be utilized for treatment of in-homogenous solid waste. Otherwise, complete inactivation of biohazardous waste cannot be guaranteed. If following this recommendation, microwave technologies having benefits in contrast to autoclaves would be more widely accepted. Another major current challenge is that biohazardous waste is often generated at many different places within one facility and then transported to the place of inactivation. Because the transport bears risks, biohazardous waste should be preferably inactivated either directly at the place where it is generated or transported in appropriate closed systems. Decentralized inactivation by the relatively simple microwave technology would be especially useful for developing countries where appropriate control of transport of waste is sometimes a challenge. Finally, the aspect of costs should also not be neglected. In comparison to the more widely used autoclave technologies, microwave irradiation is a possibility to save energy costs and has the underlying effect of a reduced carbon footprint.

Conflicts of Interest: The author declares no conflict of interest.

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