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ORIGINAL ARTICLE

Comparison of microwave and autoclave treatment for biomedical waste disinfection

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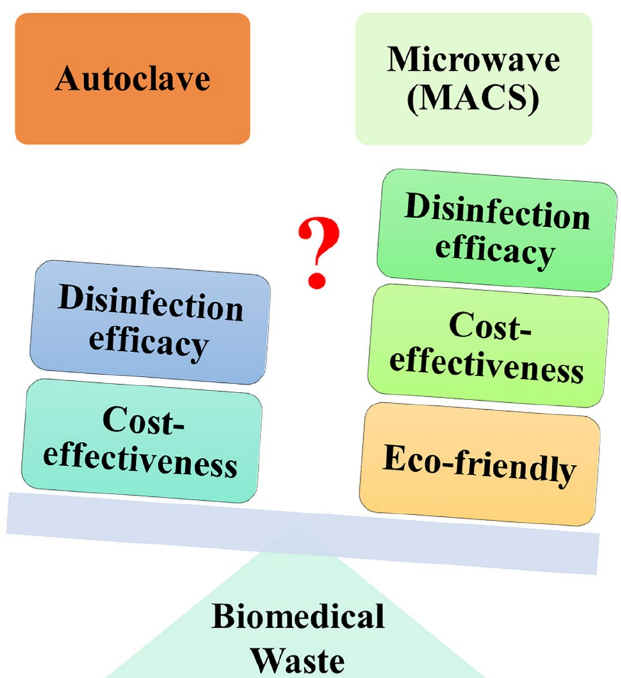
Abstract
As the world is facing a Covid-19 pandemic, this virus teaches a lesson about the importance of on-site disinfection. On-site disinfection/sterilization with real-time monitoring of biomedical waste generated from the medical facilities is mandatory to prevent hospital-acquired infection (HAI). In this study, the life cycle assessment of two technologies, i.e., microwave (radiation-based) and autoclave (steam-based) were performed to summarize the inside-out evaluation of both technologies in terms of efficiency, efficacy, and cost-effectiveness. The results of disinfection efficacy indicated a log 10 reduction (almost 100%) in the vegetative load of microorganisms compared to the control, showing a similar level of disinfection efficacy of both strategies. Additionally, both technologies were compared on several parameters, and it was discovered that the autoclave uses more time and resources than the microwave. The total cost of an autoclave to the government is approximately double that of a microwave, while the operational cost of an autoclave is more than double that of a microwave. The findings from this study indicate that MACS may be used as a dry technique of biomedical disinfection, and its portability, tunability, and compactness make it a suitable alternative for biomedical disinfection and sterilization.

Graphical abstract



Keywords Biomedical waste management · Microwave · Disinfection · Sterilization · COVID-19

Extended author information available on the last page of the article

Introduction

Managing hospital waste, especially in pandemic situations, is an important concern for the government, societies, and healthcare service providers [1–3]. Globally, human civilizations face several issues, including poverty, pandemic, pollution, population blast, and patchy developments [4–8]. These issues cause a steep growth of several challenges which need to address properly to sustain humanity. Among these issues/challenges, most governments worldwide are concerned about feeding the hungry, providing improved healthcare, and maintaining a healthy ecosystem. While healthcare institutions play a vital role in diagnosing and treating patients, they generate various biomedical waste. Because biomedical waste typically contains infectious agents and pathogens, appropriate treatment of such waste is important for protecting society from illness caused by direct or indirect contact [9, 10]. Management of waste from hospitals has several steps and methods as recommended by World Health Organization (WHO) and enforced by Central Pollution Control Board (CPCB) guidelines. The health care facilities such as hospitals, clinics for doctors, dental services, pathologies, facilities for medical research, veterinary clinics, etc., produce a bulk amount and various types of infectious waste [11, 12]. Based on composition the healthcare waste may classify as (a) general/non-infectious (85%); (b) infectious/hazardous (10%); and (c) chemical radioactive (5%) [6]. The amendment in CPCB guideline was made in 2018 based on the recommendation from the Ministry of Environment, Forests and Climate Change (MoEFCC), Government of India, in order to maintain efficient biomedical waste management (BMW), and thus to prevent the hospital-acquired infection (HAI) [7, 13]. The HAI is a significant threat while breaching the safety protocol, as occupational infection is a severe concern [14]. The majority of biomedical waste workers live in tightly populated colonies, making it easy for disease to spread. Mostly, the worker community of different industries also shares similar residence areas. Therefore, HAI may significantly impact society [15].

Infections, which are occasionally caused by multiresistant bacteria, cause a considerable impact on patients and their families in the form of illness, prolonged hospital stays, potential disability, higher expenditures, and, in rare cases, death [16]. The World Health Organization (WHO) has released a report on how best to deal with biohazardous waste generated in hospitals and other facilities working with pathogens. It says the improper handling and disposal of such waste can have a negative influence on public and occupational health and safety and the environment [3, 9, 17–19]. However, the scavenger community that works on the streets or at ultimate disposal sites is another rather substantial population exposed to the hazards posed by improperly processed health care waste (HCW) in developing countries. The untreated infectious waste is now being sent directly for incineration or finally disposed to a popular biomedical waste treatment plant. It increases the likelihood of infection during travel, temporary processing, and handling [7, 20].

Consequently, adequate and alternative technology for disinfecting healthcare infectious waste at the point of the generation before final disposal is required. To treat infectious waste, health care institutions now employ hundreds of years-old legacy technology, such as steam-based autoclaves and radiation-based microwave. The guideline strictly states that all kinds of biomedical waste must be disinfection at the generation site. The only well-known traditional methods that are now available include pyrolysis vaporization incinerator, rotary kiln incinerator, plasma incineration, chemical disinfection, and high-temperature steam disinfection (autoclave) [21–24]. However, high investment costs, a high need for technical personnel, residual disinfectants after disinfection, poor odor control, and the production of hazardous gases are all important drawbacks that should never be neglected [25]. Regardless of the technologies available, microwave-based disinfection is shown to be energy efficient, with minimal heat loss, low action temperature, quick action, low environmental pollution, and mild damage, and no residues or harmful wastes [26]. Microwave radiation with a wavelength of 3–300 mm is not a direct heat source. Through the action of resonance, the magnetron emits an electromagnetic wave with a frequency of 2.45 GHz, which is absorbed by the water molecules in the waste, increasing their agitation and, in turn, raising the temperature, causing energy to disperse as heat [27]. Meanwhile, cost analyses have recorded values of US$ 0.12/kg for microwave-treated waste US$ 1.10/kg for autoclave-treated waste [1]. These characteristics of microwave radiation make it particularly appealing as an alternative to conventional processing methods for industrial applications such as food or beverage processing, health care facilities, biotherapeutics, and so on [28, 29]. However, there is a lack of knowledge and information on the life cycle assessment of microwave-based disinfection solutions, in terms of disinfection performance, resource utilization, cost effectiveness, and environmental sustainability.

All India Institute of Medical Sciences (AIIMS), New Delhi, is an apex tertiary care teaching institute in the country and one of the most well-known and leading healthcare institutions in preventive measures for patient safety & health assessment, and biomedical waste management. Every year, tons of healthcare waste are generated at AIIMS, approximately in the yellow category (346,459 kg/ annum), red category (342,616 kg/ annum), white category (6232 kg/ annum), and blue category (353,289 kg/ annum) Table 1.

Table 1 Total waste generation in different categories of BMW management AIIMS, New Delhi, India

S. no	Month and year	Quantity of waste generated or disposed (on monthly average basis)				
		Yellow Category (Kg/month)	Red category (Kg/month)	White category (Kg/month)	Blue category (Kg/month)	General Solid waste (Kg/month)
1	May, 2017	29,253	21,622	1664	22,301	210,000
2	July, 2017	23,779	24,307	792	24,012	210,000
3	August,2017	23,902	24,118	724	25,463	210,000
4	September,2017	23,765	22,843	530	25,861	210,000
5	October,2017	23,902	23,497	654	25,167	210,000
6	November,2017	24,732	22,614	604	26,138	210,000
7	April,2018	21,761	24,462	489	26,921	210,000
8	May,2018	24,650	23,300	493	27,716	210,000
9	June,2018	26,049	24,722	450	26,847	210,000
10	July,2018	31,961	30,426	456	31,893	210,000
11	August,2018	27,847	27,592	550	29,550	210,000
12	September,2018	28,285	25,856	494	30,297	210,000
13	October,2018	29,486	25,768	580	31,351	210,000
14	November,2018	36,962	45,432	615	35,488	210,000
15	December,2018	36,603	45,761	703	34,156	210,000
16	January,2019	37,123	46,061	706	35,642	210,000
17	February,2019	31,082	43,786	623	34,235	210,000
18	May,2019	38,340	43,441.5	642.5	37,056.2	210,000
19	June,2019	37,992	42,873	602.5	36,493	210,000
20	July,2019	38,448	43,102	627	36,782	210,000
21	August,2019	51,222	56,250	1196	42,802	210,000
22	September,2019	42,824	37,604	638	36,584	210,000
23	October,2019	45,616	60,161	739.9	36,120	210,000
24	November,2019	45,125.21	59,117.6	575.5	39,121.25	210,000
25	December,2019	44,139	58,026	560.4	34,600	210,000
26	January,2020	46,044	60,207	662.6	35,139	210,000
27	Febuary,2020	43,535	58,206	564.6	31,163	210,000
28	March,2020	35,025	47,541	310.1	27,263	210,000
29	April,2020	30,001	34,100	72.05	12,209	210,000
30	October,2020	35,410	43,491	234.1	14,658	210,000
31	December,2020	35,427	43,491	237.1	14,470	210,000
32	January,2021	36,138	43,491	356.8	14,508	210,000
33	March,2021	35,568	43,491	365.4	13,465	210,000
34	April,2021	33,878	43,491	104.4	12,977	210,000
35	May,2021	60,547	59,219	547.3	9290	210,000
36	June,2021	54,279	57,644	588	15,482	210,000

As per the guidelines, the on-site disinfection of infectious waste can be performed by either method, i.e., autoclave and microwave. However, there is always a challenge or question: "Which one is more effective and efficient?" in terms of exposure duration, water consumption, consumables, Capex and Opex analysis, etc. The AIIMS, New Delhi, India procured the microwave assisted cold sterilization (MACS) technology called OptiMaser as an alternative to autoclave for their on-site biomedical waste treatment. However, certain queries were raised in terms of efficacy & cost effectiveness of microwave against autoclave sterilization technique. Therefore, the efficacy & cost-effectiveness of MACS over available methods are essential to evaluate this device as an appropriate alternative to available techniques. The present study aims to determine the comparative life cycle assessment of efficacy & cost-effectiveness of microwave and autoclaving sterilization techniques for on-site pre-treatment laboratory-based Bio-Medical waste. This research will bring new insight into how to replace the 100-year-old legacy of employing outdated methods with innovative microwave aided disinfection to battle hospital-acquired infections and secondary infections caused by improper or inadequate solid waste disposal. Meanwhile, the microwave-assisted procedure is quite beneficial for the disinfection of COVID-19 waste at the point of generation. The advantage of on-site disinfection is that it allows you to avoid the hazards of COVID waste transportation while also saving time.

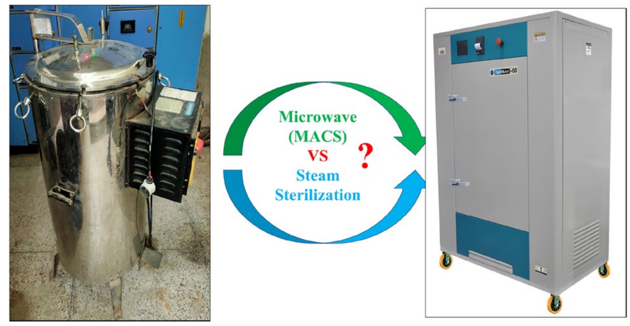


Fig. 1 Representative image of microwave and autoclave technologies

Materials and method

Chemicals

All the chemicals used in the current study were purchased from Sigma, Thermo Fisher, and Hi-media. Dehydrated culture media and their components were purchased from HiMedia and the BD Difco™. All the chemicals were of analytical grade.

Culture media

BHI (Brain Heart Infusion) media was used to grow bacteria, and SDA (Sabouraud Dextrose Agar) media was used for yeast growth. In addition, *Aspergillus flavus* sporulation was performed in PDA (Potato Dextrose Agar) slant. Approximately 0.5 mL of an overnight grown *A. flavus* was taken, and the flasks were incubated for 7 days in an orbital shaker at 200 rpm at 37 °C. The population was observed after 7 days of incubation > 90 percent of the spore, and the production of spores was observed under a microscope.

Microorganism

The effect of microwave (OptiMaser®) and the autoclave was assessed against gram-positive microbes, including *Staphylococcus aureus* (ATCC 25923) and gram-negative microscopic organisms *Escherichia coli* (ATCC 25922) and yeast strain *Candida krusei* (ATCC 6258). All microbial strains were obtained from the ATCC (American Type Culture Collection). Heat-resistant clinically isolated *A. flavus was also used in this study.* Flasks with all culture strain were incubated at 37 °C at 200 rpm for overnight.

Details of commercial microwave and autoclave

The microwave instrument was a custom design by SS Maser Technology Pvt. Ltd. with the brand name OptiMaser® Fig. 1. OptiMaser is the proprietary technology developed by the Society for Applied Microwave Electronics Engineering and Research (SAMEER) of the Government of India. In short, this device's configuration is 3 KW of magnetron power with a frequency of 2.45 GHz and a chamber capacity of 500 Liters. This instrument was procured for on-site pre-treatment of health care waste by AIIMS, New Delhi, India, in June 2017 and installed at the department of biomedical waste (BMW). The device software was installed with the dedicated cycle for biomedical waste disinfection, having the availability of tuning the condition and parameters to optimize disinfection and sterilization conditions Fig. 2.

The steam-based autoclave was procured from Bionics Scientific Technologies Pvt. Ltd. In brief, the specification of this device is 6.00 KW required power, with a temperature range of 121–134 °C and a pressure range from 15 to 17 psi (pounds per square inch) and a chamber capacity of 130 Litres. AIIMS, New Delhi, India, purchased the equipment in March 2018 for the pre-treatment of infectious laboratory biological waste and placed this in the microbiology department.

Inoculum preparation and incubation

All the desired microbes were inoculated in their respective media, i.e., BHI broth and SDA for bacterial and yeast, respectively [30, 31]. The cultures were incubated at 37 °C in an orbital shaker at 200 RPM (Rotation per minute). For bacteria, yeast, and fungal spores, the viable cell density of at least 3 McF (McFarland) as defined by Densi CHEK plus had been maintained [32]. These culture suspensions were used to validate the comparative efficacy and efficiency of autoclaves and MACS.

Preparation of samples for treatment

Infectious waste from health care has been collected from laboratories or locations. To assess the effectiveness of the disinfection against the specific microbe, the overnight culture (0.4–0.6 OD) of bacteria, yeast, and spore was diluted serially and placed in the middle position of the cavity with infectious waste [33], in both autoclave and microwave to ensure the proper radiation exposure or steam penetration. The efficacy optimized with specific

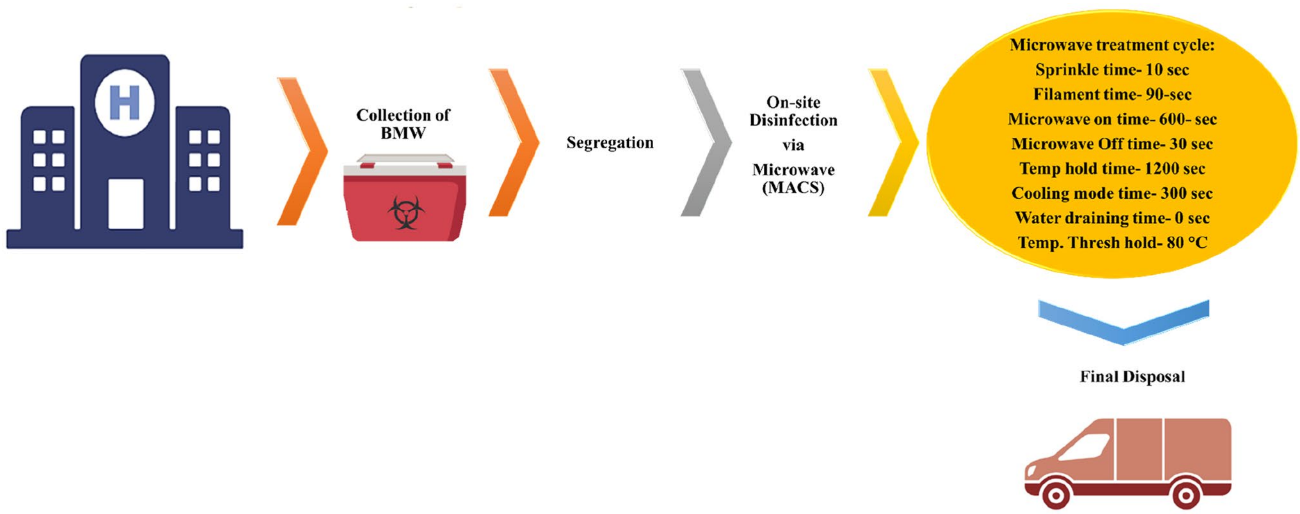


Fig. 2 Flow chart of the detailed treatment process through microwave

microorganisms and the media content and the test was also validated with hospital waste to evaluate both technologies' efficiency and efficacy.

Treatment parameters

Following inoculation, the disinfection of healthcare waste was evaluated based on the difference in microbial counts before and after exposure to the disinfection technique. To evaluate the efficacy of the machine, health care waste with different concentrations of microbes was used. Various parameters were considered in this study to evaluate the efficiency and efficacy (e. g., the weight of waste, microwave power, exposure duration, exposure period, autoclaving temperature, etc.) All microwave settings have been tweaked following our previously published article on disinfection of hospital linen [33]. The sample was exposed in a microwave cavity with a 3-KW magnetron and a 6.00-KW autoclave. To minimize parallel thermal disturbance, the bin threshold temperature was chosen at 80 °C for microwave exposure and 121 °C for steam-based disinfection. Nevertheless, exposure time, hold time, and cooling time were optimized until the desired microbial survival log reduction. In order to check the effectiveness of disinfection and sterilization, samples were kept in poly bags recommended by WHO guidelines for biomedical waste segregation and finally inside the compatible microwave bin (custom designed by SS Maser Technology Pvt. Ltd.) and autoclave cavity. The maximum running time was roughly 37.15 min for microwave exposure and 120 min for autoclave, respectively. A standard plate count method (CFU/ mL) was used to determine the effect of autoclave steam and MACS.

Evaluation of microbial viability

The efficacy of health care waste disinfection and sterilization was performed using the standard plate counting method [33, 34]. The 100 µL sample from all microbial strains was plated on the suitable medium in triplicates, with adequate untreated control. The serial dilutions prepared for each sample and 100 µL samples of 10^{-1}, 10^{-3}, and 10^{-5} dilutions were placed on a suitable medium in triplicates after completing the autoclave and MACS treatment incubated at 37 °C for 48 h. For statistical significance, three biological replicates for each species were used to assess the disinfection efficacy of MACS for the appropriate time point.

Economic feasibility assessment

Economic factors such as funding, expenditure, pricing, segregation, dumping and disposal, and management techniques play a significant role in developing a waste management system. Capital cost information, maintenance fees, operator wages, water consumption, and electricity costs for the aforementioned BMW management devices were collected using questionnaires and interviews by making assumptions with AIIMS, New Delhi, India, and SS Maser Technology responsible authorities.

Statistical analysis

Statistical analysis for CFU count, log value determination, and cost analysis were carried out using the licensed version of Microsoft office 2019 Excel Sheet (Version 19.0). The cost comparison was done using Indian government wages and standards that followed the criteria. The results were represented as microbial log reduction with three biological replicates of three independent experiment.

Results and discussion

As a result of recent legislation, Indian health care waste management is attracting more publicity for management and policy (Biomedical Waste Management and Handling Regulations, 2018). Reduced hospital acquired infections, healthy environments, reduction in costs of infection control, reduced reuse of infectious disposables, and prevention of occupational health hazards are all advantages of biomedical waste management [35]. The current condition is examined in different healthcare facilities covering various issues such as quantity and proportion of specific waste constituents, storage, treatment, and disposal methods. The potential to eliminate pathogens should, without a question, be the most important feature to consider when considering healthcare waste treatment technology. In terms of pathogen eradication, there is now compelling evidence that specifically designed microwave systems may effectively inactivate microbes [36]. Therefore, the effectiveness of disinfection (inactivation) was assessed for scenarios including complete elimination of the measured organisms.

Disinfection/ sterilization efficacy of autoclave and microwave

The efficacy of both alternative BMW management technologies autoclave and microwave was evaluated against the gram-positive microbes, including *S. aureus* and gram-negative *E. coli,* yeast strain *C. krusei,* and spore culture *A. flavus.* The specific microorganisms with healthcare waste were exposed to MACS (OptiMaser®) at 80 °C for 37.15 min (above optimized cycle) and autoclave at 121 °C for 120 min Fig. 3. The standard plate count showed that 10 log disinfection efficacies of representative bacteria, yeast, and fungal spores were achieved via both MACS (OptiMaser® 500 L capacity) and autoclave (130 L capacity) treatment. Similarly, in our previous study, we reported the highest log 10 reduction disinfection efficacy of microwave against bacteria, fungi, and yeast for linen used in healthcare facilities [33, 37]. It was inferred from the present study that both technology treatments could effectively destroy both gram-negative and gram-positive bacteria with spore culture, and there is no chance of spreading the secondary or hospital-acquired infection from the treated infectious waste at any time point. As of now, more than 1.4 million people worldwide suffer from hospital-acquired infections [38]. In 2018, 7 million infections emerged even when being hospitalized for other conditions united State hospitals, making the HAI rate a key indicator of treatment quality [39]. In developing countries, the risk of infection associated with health care is 2–20 times higher than in developed countries [39]. If not adequately managed, pathogens found in infectious waste can enter the human body by a puncture, abrasion, or cut in the skin, mucosal membrane, inhalation, or ingestion [19]. Some of the frequent ailments induced by infectious waste exposure are infection of respiratory, gastroenteric, skin, or bacteremia, hemorrhagic fevers, influenza, and viral hepatitis [6]. Therefore, alternate techniques or strategies are often needed to prevent the public from hospital-acquired infection (HAI) and secondary infection.

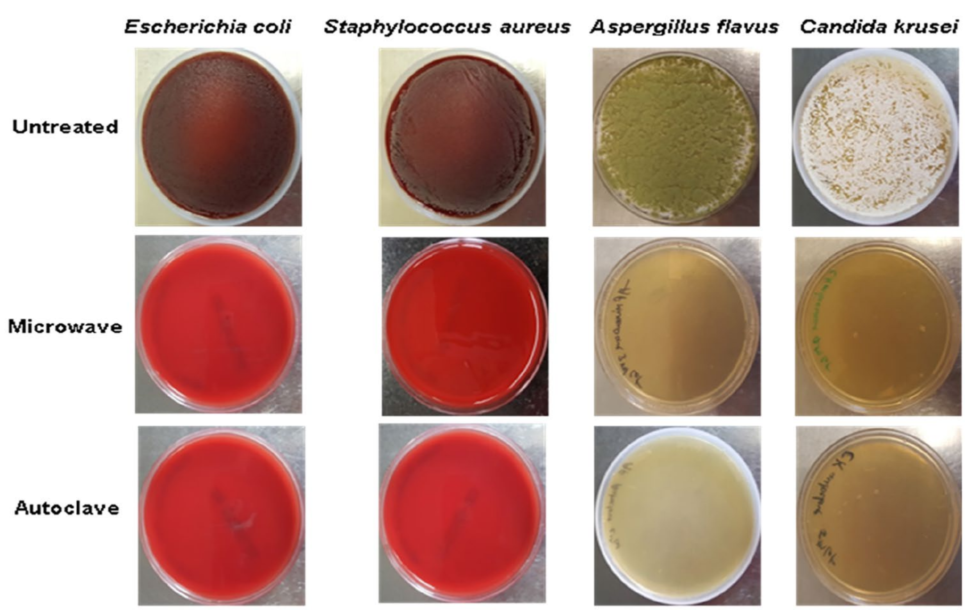


Fig. 3 Effect of microwave and autoclave on the survival of bacteria, yeast and fungi; plate showing log 10 reduction of microorganism as compared to control

The efficiency of autoclave and MACS treatment was evaluated by monitoring the mass, length of exposure, and power for each type of microbial culture. In the case of steam sterilization, both the outer jacket and the inner chamber are inserted, which are designed to withstand high pressure. Heating the outer jacket in the inner chamber wall eliminates condensation and allows steam to be used at lower temperatures. Since air is an active insulator, it is essential to remove air from the chamber to ensure heat absorption into the waste. This is achieved using the following two ways: displacement of gravity and pre-vacuuming. The temperature range that enables the eradication of spores in steam-based sterilization has been reported to be between 121 °C and 163 °C [40]. It has been reported that hazardous medical waste, including chemical, infectious, sharp, pharmacological, pathological, and cytostatic, accounted for 14% of the waste generated in Croatia from health services [41]. A case study showed that the largest sources of hazardous waste are state hospitals with a 57.9 percent generation rate [42].

In an autoclave, limitations of steam sterilizations like some plastic ware melt in the high heat, and sharp instruments often become dull. In addition, most chemical breakdowns and sticky materials cannot be treated during the sterilization cycle because they do not combine with water. It was previously reported that an autoclave should not handle anatomical and pathological waste, organic solvents, laboratory chemicals for chemotherapy waste, and low-level radioactive waste [43]. However, these kinds of restrictions are overruled in the case of microwave irradiation. MACS technology is based on the low-heat thermal process where disinfection occurs through the action of dielectric heating. The so-called loss tangent determines a substance's capacity to convert electromagnetic energy into heat at a given frequency and temperature. The loss factor is calculated as tan $d = e/e$, where e is the dielectric loss which indicates how efficiently electromagnetic radiation is converted to heat, and e is the dielectric constant, which describes the polarizability of molecules in an electric field [44]. As a result, the higher the material's loss tangent, the greater the tendency to heat up when exposed to MACS.

Aside from that, information on disinfection employing microwaving with 30-min contact durations for large-scale equipment processing 250 kg of waste per hour has been published in prior research [45]. It has been proven that microwave is based on the dielectric heating principle suggesting the disinfection is not caused by direct radiation exposure. Instead, the heat generated by the vibration of water molecules caused by the waste's dampness, which is distributed throughout the waste's bulk, inactivates the microbes [46]. However, the operational parameters of disinfection approaches in environmental assessment and the costs of HCW management scenarios were established using the operating circumstances discovered in this evaluation. Therefore, after comparing the other parameters as shown in Table 2, we can conclude that the consumption of water and electricity in autoclaves per cycle is much higher than in MACS. Similarly, the time taken by MACS for biomedical waste disinfection is much shorter (37.15 min) compared to the time taken by autoclave (120 min). During the Covid-19 epidemic, research was carried out to see if the sterilizing procedure for mask decontaminants was suitable [47]. According to the findings, the microwave at 750 W in 2 min accomplished a high level of mask decontamination while maintaining filtering breathability and efficiency, as required by the quality requirement. Similar to present study, the effectiveness of the MACS (OptiMaser-30) against sputum positive for *Mycobacterium tuberculosis* was recently reported in 2020 [48]. The percentages of acid fast bacilli (AFB) and live M. tuberculosis bacilli in the initial samples were 93.8% and 95% (approx. 94.7%), respectively, before

Table 2 A comparative specification analysis of microwave with autoclave used in AIIMS, New Delhi

S. no	Parameters	Microwave-assisted cold sterilization (MACS)	Autoclave (steam-based sterilization)
1	Basic Principle	Dielectric heating principle	Steam-based high-pressure principal
2	Mobility	Yes	No
3	Skilled Labor Required	No	Yes
4	Metal corrosion /contamination	No	Yes
5	Plastic fibre treatment	Yes	No
6	Internet hub connectivity	Yes	No
7	Process timing	45 min	120 min
8	Consumables	Nil	Pressure-sensitive tapes, bags, release effluent
9	Energy required	3 Kw/h, 16 Amp, 1Ø	6 Kw/h, 25 Amp, 3Ø
10	Chamber capacity	500 L	130 L
11	Water consumption	800 ml per cycle	130 L per cycle
12	Capex cost	Rs 24 lakhs	Rs 9 lakhs

reducing to 14.2% (32) and 1% (approx. 0.9 percent) after the microwave treatment. These findings of this study are quite similar to ours, confirming the MACS as a suitable alternative to the autoclave, particularly for isolated Tuberculosis treatment facilities in nations where sputum, a biological waste, is difficult to dispose of at the point of generation. The primary benefit of MACS is that it delivers energy directly to microwave-absorbing materials, allowing for sample volumetric heating. It is feasible to alleviate issues such as extended heating periods, temperature gradients, and energy loss to the environment by employing microwave-based sterilization [49, 50]. These characteristics of MACS make it a compelling alternative to traditional available disinfection/ sterilization technologies.

Techno-economic feasibility

Medical waste management is not simply a technical issue, but it is also heavily impacted by economic factors. Therefore, the current study carried out a comparative techno-economic evaluation based on the assumptions and provided data, as shown in Table 3. The capital cost of the microwave was found to be slightly higher than that of the autoclave, possibly due to the microwave being fully equipped with dedicated software, mobility, and Internet hub connectivity for real-time monitoring applications with less power consumption (3 Kw/h) and water (800 mL/cycle) resources. As electricity and water are interconnected and the most important resources for humans to survive, it is essential to save them for future generations. However, because of its ease of use and plug-and-play flexibility, a microwave may be operated by an unskilled worker, implying a reduction in skilled work costs compared to an autoclave.

Due to the high water consumption and complexity of autoclaves, an extra expense (i.e., 1500 Rupees/month) for water softener and secondary equipment maintenance (i.e., 4000 Rupees/month) was noticed in contrast to microwave. Furthermore, we found that the microwave requires less space (12 × 10 square feet) than the autoclave (15 × 25 square feet).

Table 3 Life cycle assessment of capital (capex) and operational (opex) cost of microwave with autoclave used in AIIMS, New Delhi

S. No	Cost parameter	Microwave 500 L chamber capacity	Autoclave 500 L chamber capacity	Assumptions based on facts from different government and private agencies
1	Initial cost	Rs.24,00,000.00	Rs.12,00,000.00	Complete setup for autoclave, ETP as per Standards of Autoclave, Schedule II GSR 343(E)
2	Power consumption	Rs.3,60,005.54	Rs.19,20,029.53	Power consumption* for 5 years (26 days a month working) taking 3 Kw 45 min per cycle for Microwave Vs 12 KW, 120 min per cycle for Autoclave (with escalation 10% per year) *Cost of Power @ Rs.10.50 per unit (4 cycles per day for Autoclave Vs 6 Cycles per day for MW)
3	Skilled labour	Rs.0.00	Rs.15,43,080.00	Rs 25,718- Salx12 months × 5 yrs # cost of labor taken as per minimum wages, Government of NCT
4	Unskilled labour	Rs.12,74,640.00	RS. 0.00	Rs 21,244 Salx12 months × 5 yrs # cost of labour taken as per minimum wages, Govt. of NCT
5	Water softener	Rs. 0.00	Rs. 90,000.00	Rs 1500 × 12 months x 5yrs *For clearing nozzles etc
6	Secondary device maintenance	Rs. 0.00	Rs. 2,40,000.00	Rs 4000 × 12 months x 5yrs *For maintenance of boilers, R.O system etc
7	Maintenance electro mechanical	Rs.90,000.00	Rs.2,40,000.00	At the rate of Rs 4000 × 12 mthsx5yrs for Autoclave At the rate of Rs 1500 × 12 mthsx5yrs for Microwave
8	Space required	Rs.4,45,500.00	Rs.13,77,000.00	Rental of space required (12*10 Sq. Ft for MW @ 675/m^2/month; 15*25 Sq. Ft for MW @ 675/m^2/month), as per OM. F.No.18015/1/2017-pol.III issued by Directorate of Estate, M/o of Urban Affairs,
9	Total Opex for 5 years	Rs.21,70,145.54	Rs.54,10,109.53	Total operation & maintenance cost over a period of 5 years
10	Capex + Opex for 5 years	Rs.45,70,145.54	Rs. 66,10,109.53	
11	Residual value	Rs.14,39,268.86	Rs.4,91,520.00	after 5 years
12	Total cost to Government exchequer in 5 years	Rs.31,30,876.67	Rs. 61,18,589.53	Total cost to Government Exchequer is nearly 2 times that of a microwave
13	Capex cost	Rs.24,00,000.00	Rs.12,00,000.00	
14	Opex cost	Rs.21,70,145.54	Rs.54,10,109.53	Autoclave Opex is more than 2 times that of running a microwave

The autoclave operates on the pressure principle and emits water vapors, needing a separate chamber for waste treatment and resulting in high operating costs. In position, the microwave provides a safe, plug-and-play feature, making it easier to use anytime, anyplace, and recommending the microwave for small healthcare facilities with low-cost maintenance. It can be concluded from Table 3 that the initial cost of the microwave device is high. However, the running or operating cost of the microwave is more than two times less than that of the autoclave. Thus, the cost-effectiveness of microwave (MACS) technology over autoclave technology is significant economically.

Similar to this study in 2013, Soares et al. examine the three methods presently utilized in healthcare facilities to treat infectious waste, namely microwave, autoclave, and lime (depending on the type and load capacity)[1]. According to their cost–benefit analysis, the microwave scenario was superior since its waste treatment equivalent cost was INR 9.18 per kg of waste instead of the autoclave scenario (INR 84.16 per kg of waste) and lime scenario (INR 117.05 per kg of waste). After comparing these scenarios, it was discovered that the operating cost is approximately ten times cheaper than that of steam heat sterilization or an autoclave. Similarly, Tudor et al. (2009) reported prices in the INR 35930.33–47932.58 per tonne range for alternative approaches (e.g., sterilization) compared to other high-temperature treatments (e.g., incineration) in the INR 59858.39–95788.72 per tonne range [51]. Likewise, Karagiannidis et al. [52] conducted a documentation review of Greek hospitals and found that the expenses of disinfecting healthcare waste ranged from US$ 0.71 to 2.40/Kg [52].

Following a discussion of the current investigation and the available data, overall, the significant practical impact of the present study clearly indicates that MACS can be an adequate, economical, and alternative to the typical steam heat sterilization approach. Microwave technologies provide promising clean solutions for those healthcare facilities seeking operational excellence and sustainable resources in line with United Nations (UN) goals and WHO initiatives in reducing infections worldwide, global warming, and energy/water consumption, and are quickly becoming the leading cutting-edge solution for biomedical waste management. Furthermore, this method may be used to other industries such as food and dairy, where disinfection or sterilization is a must but resources are scarce. It may also be used as an alternative for the sterilization of personal protective equipment, which is the first line of defense, in a pandemic event.

Conclusions

The healthcare industry constantly progresses and evolves, which generates both opportunities and problems. This study observed the disinfection efficiency of upto log 10 against microorganisms after microwave and autoclave treatment separately. However, results from the economic and environmental point of view revealed the superiority of microwave technology in terms of cost-effectiveness and eco-friendliness over the autoclave. Additionally, the resource utilization such as water and electricity consumption were significantly lesser (800 mL/cycle and 3 Kw/h) than autoclave (130 L and 6 Kw/h). Meanwhile, the space required for the installation of MACS is also significantly less than autoclave. These findings indicate the use of game-changing technology (microwave) for on-site solutions for medical waste disinfection and sterilization with real-time monitoring to avoid any violation of safety during interim processing in the facility and transport of medical waste from the hospital to the treatment site. The indigenously developed microwave device (MACS) is made in such a way that it usually negates all sorts of drawbacks and problems associated with the disinfection and sterilization of infectious medical waste at the point of generation. Therefore, this technology may be used in the healthcare sector and in other public and government sectors where resources are limited, and the need for disinfection and sterilization of products and goods is high, such as the food and agricultural industries.

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Declarations

Conflict of interest The authors declare no competing interests.

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