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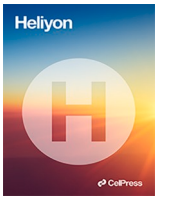

Research article

Microbial inactivation and emission of volatile organic compounds in low-heat thermal treatment of infectious healthcare waste

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ABSTRACT

The growing use of low-temperature waste decontamination devices in hospitals has raised concerns about their inactivation efficiencies and emissions of volatile organic compounds (VOCs). This study evaluated the decontamination efficiencies, as well as VOC and ammonia emissions, of sterilizer devices in four hospitals, including two autoclaves (one with a shredder and one without), a hydroclave, and a dry heating device. Decontamination efficiency was assessed using mechanical and biological indicators, while air pollutants, including VOCs and ammonia, were measured according to National Institute for Occupational Safety and Health (NIOSH) methods. Evaluation of decontamination revealed that the autoclave with a shredder achieved the highest efficiency (up to 100 %), highlighting the importance of shredding, while the autoclave without a shredder demonstrated the lowest performance. Maintaining an appropriate temperature was also identified as a reliable indicator of device efficiency. The hydroclave exhibited the highest VOC and ammonia emissions (128.03 mg/m^3 for VOCs and 6.48 mg/m^3 for ammonia), while the autoclaves had the lowest ones (45.72 mg/m^3 for VOCs and 2.58 mg/m^3 for ammonia). The three major VOCs emitted from the sterilizer devices included dichloromethane, ethyl alcohol, and ethyl acetate (with a total level of 22.82 mg/m^3). VOC and ammonia emissions were affected by device operational factors and waste composition. These findings highlighted the critical need to optimize hospital waste management practices. Adhering to operational parameters that directly influence device efficiency, along with equipping low-temperature sterilization devices with air pollutant control systems, can significantly minimize emissions, thereby reducing occupational health risks and environmental impacts.

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1. Introduction

The growth of the population in recent decades has resulted in heightened human activities, changes in lifestyle, consumption patterns, and ultimately an upsurge in waste production. The rise in population has also led to an increase in healthcare facilities, subsequently causing a surge in the production of healthcare waste. Healthcare waste encompasses all waste generated during various stages of medical care, treatment, research, diagnosis, and laboratory procedures. This waste is classified into two categories based on potential harm: non-hazardous waste, which constitutes 75–90 % of the total, and hazardous waste, comprising 10–25 % of the total [1,2]. The World Health Organization (WHO) categorizes hazardous healthcare waste into nine distinct groups, including infectious waste, pathological waste, sharps, pharmaceutical waste, genotoxic waste, chemical waste, waste containing heavy metals, pressurized containers, and radioactive waste [3].

Infectious waste forms a significant proportion of hazardous healthcare waste and includes materials potentially harboring pathogens capable of spreading infectious diseases. This category comprises blood products, isolation ward waste, microbial cultures, pathological waste, contaminated sharps, animal carcasses, bedding, surgical and autopsy residues, laboratory waste, dialysis waste, and contaminated equipment [4,5]. Although hazardous waste constitutes only a fraction of total healthcare waste, improper management—particularly of infectious waste—can result in the transmission of dangerous infections among healthcare workers, waste handlers, and the broader community. This not only jeopardizes individual health but also places additional strain on healthcare systems [6,7].

Improper disposal of infectious waste can introduce antibiotic-resistant microorganisms into the environment, heightening the public health risk by worsening the global antibiotic resistance crisis. Insufficient microbial inactivation during waste processing can allow pathogens to persist and undergo genomic changes, enhancing their resistance [8,9]. Additionally, improper waste management poses environmental risks, as pathogens can infiltrate natural ecosystems, impacting wildlife and disrupting ecological balances. Pollutants released from these wastes may also contaminate soil, water, and air. Thus, adhering to strict protocols for waste segregation, collection, transport, and final disposal, such as sterilization or incineration, is crucial to protect both public health and the environment by reducing the spread of infectious diseases and antibiotic resistance [8,10].

Effective waste management requires steps such as segregation, collection, and appropriate treatment methods, including thermal decontamination using devices like autoclaves and hydroclaves [11,12]. The decontamination of infectious waste is a critical component of healthcare waste management and is categorized into low-heat and high-temperature methods. While incineration effectively destroys pathogens, improper control can result in the release of toxic pollutants such as dioxins, furans, heavy metals, and greenhouse gases [13,14]. Low-heat decontamination methods, operating at 121–155 °C, offer advantages including lower energy consumption, reduced operational costs, and minimized environmental pollutants, with the potential to achieve a six-log (99.9999 %) microbial reduction. However, these methods face challenges such as high equipment costs, higher energy consumption, uncertainty about uniform steam penetration, and emission of environmental pollutants. Waste pre-treatment such as shredding can further improve efficiency of low-heat decontamination methods. For instance, a study by Maamari et al. [15] showed that shredding reduced treatment time at 144 °C from 20 to 10 min. Rigorous monitoring of parameters such as temperature, pressure, and biological indicators is essential to ensure their reliability and effectiveness [16,17]. Studies in Iran, including Yusefi et al. [18] reported complete microbial inactivation during infectious waste treatment, whereas Fahiminia et al. [19] observed microbial regrowth, highlighting the inconsistent effectiveness. International research aligns with this inconsistency; Yaman et al. [20] and Park et al. [21] both found significant reductions in *Bacillus stearothermophilus* using steam-based autoclaves, achieving a 6-log inactivation (99.9999 %).

Although emissions of toxic air pollutants from low-heat technologies are considered to be negligible, inadequate segregation of toxic materials, such as antiviral drugs, in medical waste can lead to the elevated release of volatile organic compounds (VOCs), including benzene, toluene, ethylbenzene and xylene (BTEX), alcohols, phenols, and aldehydes during the process. Additionally, the operational conditions of low-temperature sterilizers, such as temperature and pressure, can alter the molecular structure of organic materials, generating pollutants such as formaldehyde, acetone, and styrene [22–27]. The emissions of toxic air pollutants from low-heat technologies pose health risks, including nasal and throat irritation due to mucosal membrane stimulation, systemic effects like fatigue and impaired concentration, and toxic effects such as carcinogenicity [28–30].

Despite Iran's Ministry of Health and Medical Education (MOHME) mandating use of low-heat technologies for infectious waste, emissions from these devices, particularly air and wastewater pollutants, are insufficiently monitored [31]. In Iran and globally, limited research has examined the emission of hazardous air pollutants from waste sterilization devices and the associated air pollution risks in infectious waste decontamination areas. Given the sensitivity of the hospital environment, the constant presence of diverse individuals, the wide range of sterilizer types and brands, and the varying skill levels of their operators, addressing air pollutant emissions is essential. These emissions must be considered alongside commonly monitored parameters, such as the microbial load reduction in decontaminated waste, to ensure comprehensive safety evaluations. To address these critical concerns, this study aimed to compare the performance of four low-temperature infectious waste sterilization devices—autoclave with shredder, autoclave without shredder, hydroclave, and dry heat systems—in terms of their decontamination efficiency and the emission of hazardous air pollutants, including VOCs and ammonia (NH_3). By quantifying emissions and evaluating the decontamination effectiveness of these devices, this research provides an integrated assessment of emission and operational efficiency.

2. Methods

2.1. Device selection and justification for comparative analysis

The research focused on two main objectives: (1) evaluating the decontamination effectiveness of healthcare waste sterilizer devices, and (2) identifying and quantifying VOCs and NH_3 in the indoor air surrounding these devices. This study was conducted over a period of 8 months, covering different seasons and spanning two distinct phases: before and during the COVID-19 pandemic. In alignment with Iran's MOHME policy and commitment to the Stockholm Convention, to prevent the release of persistent organic pollutants (POPs), hospital incinerators were replaced with lower-temperature sterilizer devices for healthcare waste. Currently, among the 151 hospitals in Tehran with sterilizer devices, 63 % use autoclaves, 11 % hydroclaves, 7 % dry heat devices, and 19 % chemical treatment systems. To provide a comprehensive comparison of these technologies, four hospitals equipped with three types of low-temperature sterilizers were selected: an autoclave with an internal shredder, an autoclave without shredder, a hydroclave, and a dry heat device—were selected and designated as hospitals A, B, C, and D, respectively. These types represent the most commonly used sterilization technologies in Tehran's hospitals and were chosen to allow assessment of both the decontamination efficiency and the emissions produced during waste treatment. The hospitals were selected based on accessibility and the diversity of their sterilizer devices, ensuring the study captured different technological approaches of waste decontamination within the available timeframe and resources [32,33].

2.2. Hospital waste quantification and characterization

To collect data on the quantity and quality of hospital waste, a questionnaire was used, which was completed by the environmental health officer. The questionnaire contained questions regarding the hospital type, the number of beds, and the physical characteristics of the facility (including the location and size of the building, isolation conditions, ventilation system, etc.), operational conditions (such as the number of daily shifts, waste handling procedures, and waste segregation practices), and operator characteristics. The data obtained from this questionnaire provided general information on the quantity and type of waste generated at each hospital. Data on waste generation rates and storage methods were crucial for assessing sterilizer device efficiency and identifying potential sources of airborne pollutants during waste treatment.

2.3. Performance monitoring of healthcare waste sterilizer devices

The performance monitoring of healthcare waste sterilizer devices included two complementary methods: mechanical monitoring and biological monitoring. These methods allowed for a comprehensive assessment by covering both operational parameters and microbial decontamination efficiency. The first method was mechanical monitoring, which this method provided a baseline operational assessment by recording key parameters such as pressure, temperature, and exposure time, as well as testing steam penetration using the Bowie-Dick test (40 tests). The second method was biological monitoring, using indicators based on the ATCC7953 and NIZO4225 test methods. *Bacillus stearothermophilus* vials were used for monitoring hydroclave and autoclave devices, while the dry heating sterilizer was assessed using STERIDRY-test glass indicators containing *Bacillus atrophaeus* ATCC9372, manufactured by LTA, Italy (40 tests) [29,34]. The third method was microbial culture for biological monitoring (40 tests), using the surface culture method with Tryptone Soy Agar (TSA) medium. These methods were selected to provide a complete assessment across various sterilizer technologies, as each method is specifically suited to the operational characteristics and decontamination processes of the devices being tested. The monitoring practices followed guidelines from the Health Reference Laboratory of the MOHME [8,26], ensuring reliable and standardized results across devices [19,35].

2.4. VOCs and NH_3 emission measurement in healthcare waste sterilizer devices

In the second part of the study, VOCs and NH_3 concentrations were measured in the vicinity of healthcare waste sterilizer devices. Air sampling was conducted in two stages: (1) during the decontamination cycle and (2) after waste unloading. For each device, ten air samples were collected using SKC air sampling pumps, calibrated with a digital calibrator to ensure accuracy. VOCs were sampled using coconut shell charcoal absorbents at a flow rate of 0.2 L/min, following the National Institute for Occupational Safety and Health (NIOSH) 1501 method. Samples were transported in coolbox to the laboratory, where VOCs were desorbed using carbon disulfide and analyzed with gas chromatography/mass spectrometry (GC-MS) method. This method was selected for its suitability in measuring organic compounds typically emitted by sterilizer devices. For measuring NH_3 concentration, the NIOSH 6015 method was employed. NH_3 was collected on a solid sorbent tube (sulfuric acid-treated silica gel), and its concentration was determined through colorimetric analysis of indophenol using visible light spectrophotometry [23,25,36]. Additionally, real-time measurements of VOCs and NH_3 were performed with a PhoCheck Tiger analyzer, model ITS09ATEX26890X (Ion Science, 2019). Environmental parameters such as atmospheric pressure, temperature, relative humidity, and ventilation rate were recorded during sampling. The VOC and NH_3 sampling setup was designed to simulate human exposure, with absorbent tubes positioned at a height of 1.5 m to approximate the breathing zone.

2.5. Data analysis methodology

Data analysis was performed using SPSS software version 29. Initially, operational parameters and results from mechanical and biological monitoring were analyzed to assess each device's decontamination performance. Additionally, measurements of VOCs and NH_3 emissions, along with recorded environmental parameters, were statistically analyzed to explore potential correlations between device operation and pollutant release. Finally, the results from all four devices were compared to identify performance variations and emission differences.

3. Results and discussion

3.1. Quantity and composition of healthcare waste

Table 1 presents the total waste generated in the studied hospitals. The total waste generated in the studied hospitals consisted of 5282 kg/d of general waste, 3763 kg/d of infectious and sharp waste, and 111 kg/d of pharmaceutical and chemical waste. Comparative studies of hospital waste show that waste generation varies widely across countries, influenced by local healthcare practices, regulatory standards, and waste management systems [16,28]. With 1889 active beds across these hospitals, the average daily waste generation per bed was 2.79 kg for general waste, 1.99 kg for infectious and sharp waste, and 0.06 kg for pharmaceutical and chemical waste (Fig. 1). These values are similar to those reported in some regions but notably higher than global estimates [7,17]. Healthcare waste generation rates vary widely around the world. The WHO estimates the global average daily per capita production of general and infectious waste to be 2.0 and 0.5 kg per active bed, respectively. However, several studies have reported higher levels, which are likely attributable to factors such as inadequate waste separation, suboptimal reduction practices, and institutional inefficiencies in waste management [37–39].

As shown in Fig. 1, the amount of healthcare waste in the studied hospitals exceeded the global average but was below the average for high-income countries. Waste generation is a key indicator of waste management effectiveness, influenced by several factors, with proper management practices playing a critical role in determining both the volume and types of waste generated. Based on the results from the studied hospitals, the average waste generation was 4.85 kg/occupied bed per day. Minoglou et al. [40] examined the differences in hospital waste generation across various countries and its correlation with socioeconomic conditions and environmental factors. Their findings highlighted significant regional variations, with higher waste generation typically observed in countries with advanced healthcare systems, such as those in North America and Europe, compared to lower-income countries in Africa and parts of Asia. The results of this research aligned with those of studies conducted in Bushehr (4.39 kg/occupied bed/d) [41] and Isfahan hospitals (4.1 kg/occupied bed/d) [42]. However, other studies reported different figures, with Tehran hospitals averaging 3.45 kg/occupied bed/d [43], and Kashmar and Sabzevar reporting 3.19 and 2.59 kg/occupied bed/d, respectively [44].

Finally, in comparison with the results of the research conducted in Portugal by Lee et al. (3.8 kg/occupied bed/day) [45], Italy by Ferraz et al. (3–5 kg/occupied bed/day) [46], Turkey by Yaman et al. (1.19 kg/occupied bed/day) [20], it is evident that waste management methods play a more significant role in determining hospital waste generation than other factors and, this highlights the need for waste management improvements that address specific local challenges, such as inadequate waste segregation and reduction practices.

The average infectious waste in the four hospitals was 1.99 kg/occupied bed/d (ranging from 1.45 to 3.83 kg), significantly exceeding the WHO's recommended limit of 0.5 kg/occupied bed/d. For comparison, studies by Manar et al. in India [47], Zhang et al. in China [48], and Ebrahimi et al. in Iran [49] reported infectious waste amounts of 0.56 kg, 0.79 kg, and 1.15 kg per occupied bed per day, respectively.

The ratio of general to total healthcare waste further underscores the inadequacy of waste management practices in the hospitals studied. On average, general waste constitutes only 58 % of the total healthcare waste in the studied hospitals, which is significantly lower than the WHO's recommended level of 75 % for general waste in healthcare facilities [29]. In countries where infectious waste represents a smaller proportion of total waste, effective segregation practices have shown success [33,40]. According to Fadaei's study [32], only about 25 % of countries practice waste segregation, and just 17 % use standardized storage for all types of medical waste [50]. This discrepancy highlights the pressing need for improved waste management strategies, especially in Hospital B, where general waste made up only 37 % of the total healthcare waste.

Table 1
Types and amount of health care waste in selected hospitals.

Hospital	Active Bed	General waste			Infectious & Sharp waste			Pharmaceutical & Chemical waste		
		Weight (kg)	Percentage (%)	Per Capita (kg/bed.d)	Weight (kg)	Percentage (%)	Per Capita (kg/bed.d)	Weight (kg)	Percentage (%)	Per Capita (kg/bed.d)
A	481	1000	58	2.08	700	40	1.45	33	2	0.07
B	926	3000	62	3.24	1800	37	1.94	43	1	0.04
C	286	282	35	0.98	513	63	1.79	18	2	0.06
D	196	1000	57	5.1	750	42	3.83	17	1	0.08
Total	1889	5282	–	–	3763	–	–	111	–	–
Average	–	–	–	2.79	–	–	1.99	–	–	0.06

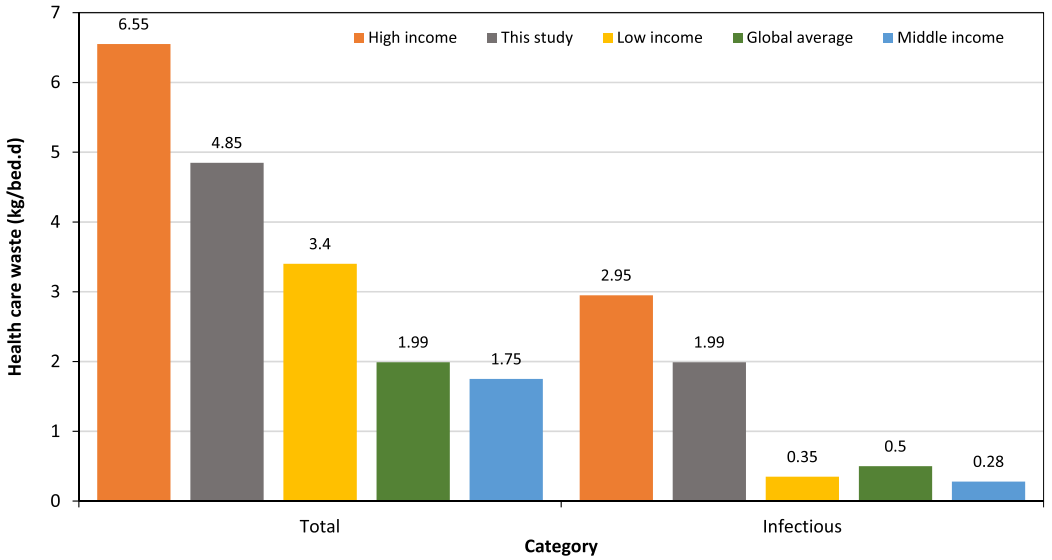

Fig. 1. Comparison of total and infectious healthcare waste production in the studied hospitals, global average, high-income, middle-income and low-income countries.

3.2. *Decontamination efficiency of sterilizer devices*

Fig. 2 shows the compliance with standard operating conditions (pressure, time, and temperature) in the low-heat thermal treatment methods of infectious healthcare waste. Each sterilizer device operates within specific ranges of temperature, pressure, and time, and adherence to these ranges is crucial for optimal performance. In this study, monitoring revealed that of 30 runs for pressure and 40 runs for time and temperature, 13 runs did not maintain the appropriate operating pressure, 3 runs did not meet the standard operating time, and 4 runs failed to reach the required temperature. With the exception of pressure, the sterilizer devices demonstrated good mechanical performance, achieving compliance rates of 56.7 % for pressure, 92.5 % for time and 90.0 % for temperature. Pressure steam sterilization technology, for example, processes crushed medical waste at 121 °C for 20 min under 100 kPa pressure, as described by Giakoumakis et al. [16] maintaining these conditions is critical for steam to penetrate the waste effectively, denature microbial proteins, and ensure safe disposal. Strict monitoring of these parameters is essential to ensure effective sterilization and responsible waste disposal [16,21].

According to Fig. 2, the dry heating system demonstrated the highest compliance at 90 % under optimal operating conditions, while

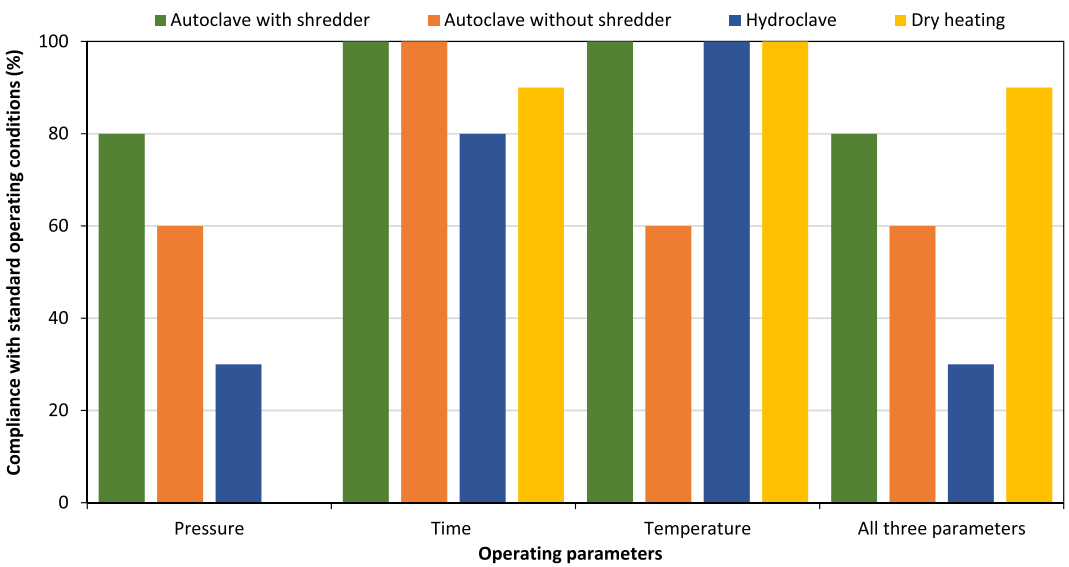

Fig. 2. Compliance with standard operating conditions (pressure, time, and temperature) in low-heat thermal treatment methods of infectious healthcare waste.

the hydroclave system showed the lowest compliance at just 30 %. The hydroclave device sterilizes medical waste using pressurized steam at high temperatures (121–135 °C), with the high pressure and temperature of the steam denaturing proteins and destroying microorganisms and viruses. However, these defects in mechanical performance suggest that sterile conditions may not be consistently achieved throughout all areas of the chamber, as the steam may not penetrate uniformly [13,15].

Fig. 3 illustrates the decontamination efficiency of sterilizer devices based on biological monitoring using vials and microbial culture methods. As can be seen in Fig. 3, based on indicator vials the autoclave with shredder achieved a remarkable 100 % decontamination rate (indicated by negative culture results), followed by the hydroclave at 90 %, the dry heating device at 80 %, and the autoclave without shredder at a mere 30 %. When evaluated through microbial cultivation, the effectiveness was slightly different, with the autoclave with shredder still leading at 90 %, while the hydroclave maintained its performance at 90 %, the dry heating device scored 60 %, and the autoclave without shredder dropped to just 10 %. Overall, the autoclave with shredder emerged as the most effective for decontaminating infectious waste, while the autoclave without shredder demonstrated the least effectiveness.

The effectiveness of sterilizer devices, as highlighted by Ahmed Khan et al. [17], is influenced by both their design and operational parameters. Zulqarnain et al. [51] introduced the evaluation based on distance from average solution (EDAS) method as a structured framework for evaluating sterilization systems based on criteria such as pathogen reduction, energy consumption, VOC emissions, and costs. By combining criteria, decision-makers can develop a reliable framework for selecting sterilization technologies that balance technical feasibility and microbiological safety. Mazzei and Specchia [13] highlighted the use of multi-criteria decision analysis (MCDA) to evaluate technologies based on waste type, emissions, and technological readiness levels (TRLs). While advanced methods like gasification plasma require further optimization, established technologies such as autoclaves, steam sterilizers, and incinerators have higher TRLs and broader adoption.

Given the inconsistent findings between mechanical and biological monitoring in sterilizer devices, a statistical analysis was conducted to examine the relationship between mechanical operating parameters and biological decontamination efficiency. The chi-square test revealed a significant relationship between temperature compliance and biological outcomes for both vials (p value = 0.015, $\chi^2 = 5.926$) and microbial cultures (p value = 0.006, $\chi^2 = 7.407$). Other parameters, including pressure and time compliance, showed no significant relationships with biological indicators.

The existing literature on the evaluation of sterilizer device efficiency presents conflicting results based on physical, chemical, and biological assessment criteria. Bayat et al. [43], Rafiee et al. [31], and Yousefi et al. [18] reported near-perfect efficiency based on biological indicators, while Fahiminia et al. [19] found 95 % efficiency for autoclaves without shredders, compared to 10%–30 % in the current study. Farshad et al. [52] observed 100 % efficiency for autoclaves with shredders and dry heating devices, but only 50 % and 80 % decontamination efficiency for autoclaves without shredders and hydroclaves, respectively. Adding to this heterogeneity, Malakootian et al. [53] highlighted varying sterilizer efficiencies of 96.3 %, 85.3 %, and 84.0 % based on mechanical, chemical, and biological indicators, respectively. Consistent with this study, Dursan et al. [54] and Mamari et al. [15] favored autoclaves for decontaminating infectious waste, whereas Salkin et al. [55] found them unsuitable. Miranzadeh et al. [56] emphasized temperature and operating time as key factors for efficiency but noted that waste packaging and loading had no impact. Variability in performance may also result from factors such as device wear, calibration issues, overloading, and insufficient monitoring. Reducing infectious waste generation may address operational challenges effectively.

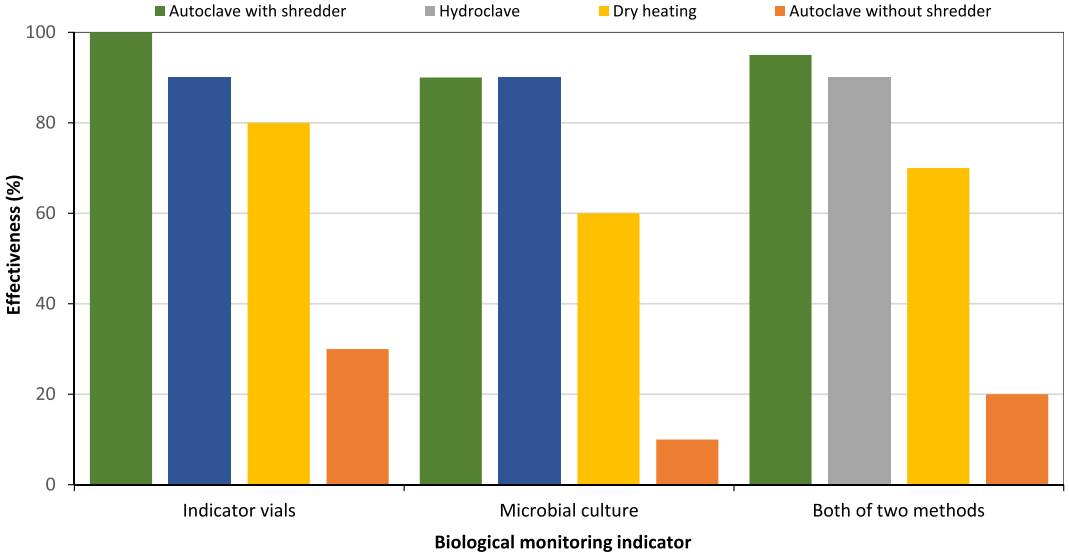

Fig. 3. Comparison of the decontamination efficiency of sterilizer devices based on biological monitoring using vials and microbial culture methods.

3.3. VOC and ammonia emissions from sterilizer devices

Air pollutant compounds (VOCs and ammonia) were measured before and after the operation cycle of the sterilizer devices. Fig. 4 displays the VOC and ammonia concentrations in the indoor air before and after use of the sterilizers. As shown in Fig. 4, the total concentration of VOCs and ammonia emitted by the hydroclave (134.51 mg/m^3) was significantly higher than that of other sterilizer devices (49.13, 58.97, and 55.35 mg/m^3 for the autoclave with shredder, autoclave without shredder, and dry heating, respectively) after the operation. In contrast, before the start of operation, these air pollutant concentrations were much lower, ranging from 4.10 mg/m^3 in the autoclave with shredder to 32.75 mg/m^3 in the hydroclave. The pair *t*-test was conducted to compare the mean concentrations of VOCs and ammonia before and after the use of sterilization devices in hospitals A, B, C, and D. The results indicated that in all hospitals, the differences in mean concentrations were statistically significant (p value < 0.001).

According to Fig. 4, the hydroclave demonstrated the highest mean VOC concentration at 128.13 mg/m^3, while the autoclave with shredder had the lowest mean concentration at 45.72 mg/m^3. To analyze differences in the mean VOC concentrations among the sterilizer devices, a one-way analysis of variance (ANOVA) was performed. The results indicated statistically significant differences in mean VOC concentrations across the devices (p value < 0.05). These differences are attributed to variations in the design and mechanisms for pollutant management in these devices. The autoclave with shredder effectively reduced VOC concentrations in the surrounding environment by discharging a substantial portion of the pollutants into the sewage system through its internal shredding mechanism. In contrast, although the hydroclave employed a similar discharge mechanism, its inefficiency in pollutant evacuation likely resulted in higher VOC emissions into the surrounding environment.

As can be seen in Fig. 4, the mean concentration of ammonia in the vicinity of the hydroclave was the highest among the studied devices, measured at 1832 μg/m^3 before operation and 6483 μg/m^3 after operation. The average ammonia concentrations emitted by the autoclave with a shredder, the autoclave without a shredder, and the dry heat system were recorded as 3407 μg/m^3, 2585 μg/m^3, and 4035 μg/m^3, respectively; however, statistical analysis using the ANOVA test revealed no significant differences among the devices. These findings align with the study by Dengchao et al. [25], which reported that steam-based systems generally produce higher levels of ammonia compared to microwave and chemical processes. The ammonia originates from nitrogen-containing compounds in infectious waste, which decompose during microbial activity and under high heat and pressure conditions [57]. Moreover, insufficient ventilation can exacerbate ammonia concentrations [58].

The low-heat thermal technologies methods, although producing less air pollution than incineration, still emit pollutants due to the high temperatures and pressures involved. A portion of these gases is discharged into the sewer, while the remainder is released into the indoor environment upon opening the sterilizer, posing health risks to workers and the public if adequate air pollution control systems are not in place [22,26,59]. Farzadkia et al. [23] and Ostadi et al. [60] showed that the emission rates of VOCs increased with the operational lifespan of sterilizer devices. Dengchao et al. [25] examined VOC content and formation mechanisms in non-incineration waste treatment systems, including steam-based, microwave-based, and chemical disinfection methods. They found that total VOC emissions were higher in steam-based systems compared to the other two methods, although odor generation was notably lower, favoring steam-based systems for odor control. This analysis underscores the importance of selecting appropriate waste treatment technologies and emphasizes the critical need for optimizing the design, operational efficiency, and management of sterilizer devices to effectively reduce pollutant emissions and improve environmental safety [16,26,38].

Fig. 5(A–D) presents the concentrations of various groups of VOCs, including oxygenated, halogenated, aromatic, and hydrocarbon

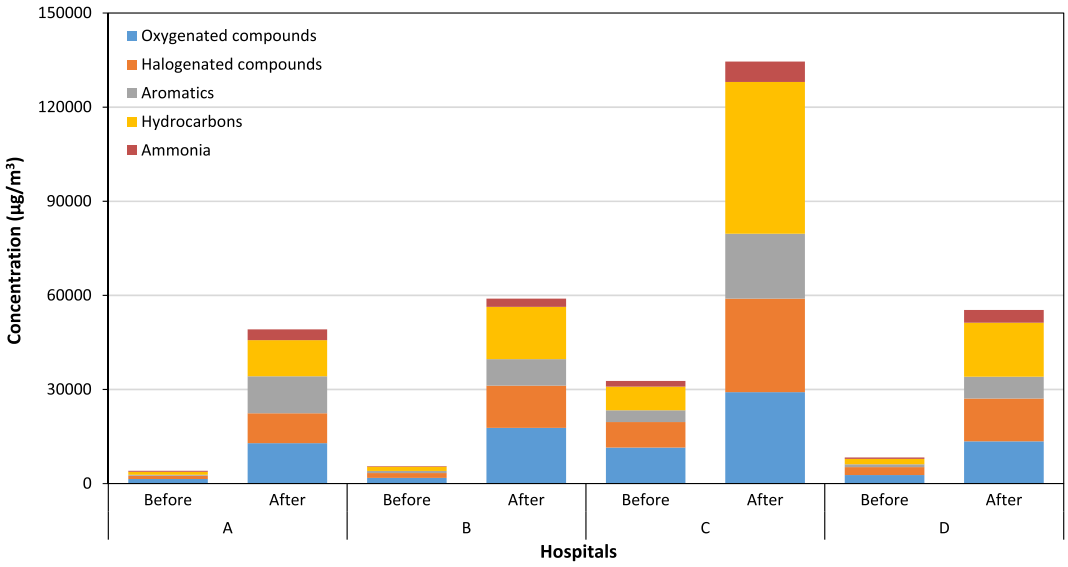

Fig. 4. Comparison of the total concentration of pollutant compounds in the indoor air before and after use of the sterilizers (A: Autoclave with shredder, B: Autoclave without shredder, C: Hydroclave and D: Dry heating).

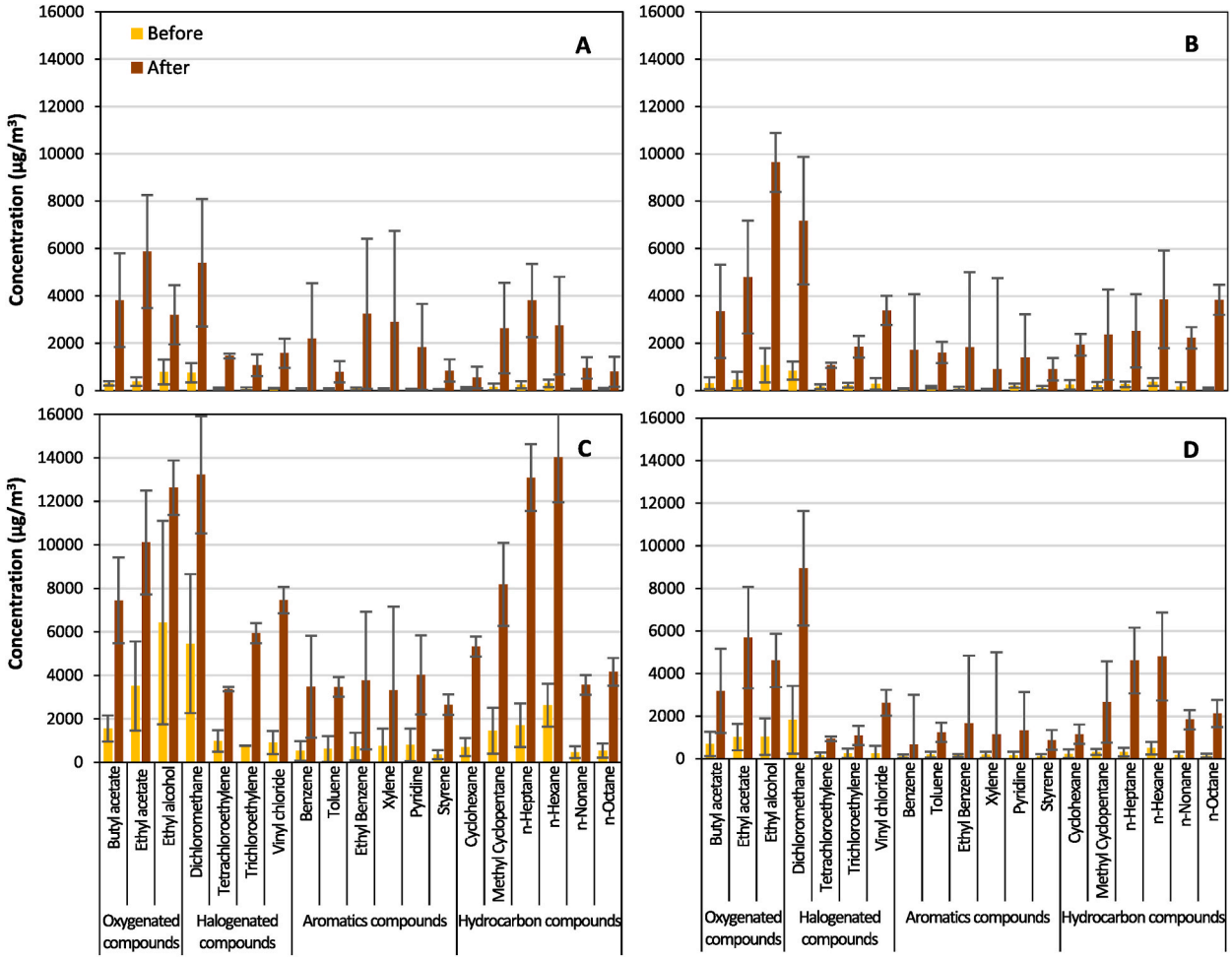

Fig. 5. Contributions of the compound groups in the total average air concentration of VOCs in the vicinity of sterilizer devices before and after operation (A: Autoclave with shredder, B: Autoclave without shredder, C: Hydroclave and D: Dry heating).

compounds, in the vicinity of sterilizer devices. The relative concentrations of these compounds vary across the different devices. In the autoclave with shredder (Fig. 5(A)), the VOC concentrations decreased in the following order: oxygenated, aromatic, hydrocarbon, and halogenated compounds. In the autoclave without shredder (Fig. 5(B)), the order of pollutant emissions was oxygenated, hydrocarbon, halogenated, and aromatic compounds. In the hydroclave (Fig. 5(C)), the sequence of pollutant groups was hydrocarbon, halogenated, oxygenated, and aromatic compounds. Similarly, the dry heat sterilizer (Fig. 5(D)) exhibited the same pattern of VOC emissions as the hydroclave. The average proportions of the identified gaseous compounds (calculated across all four devices) consisted of 30.69 % hydrocarbons, 24.0 % oxygenated compounds, 21.7 % aromatic compounds, and 15.7 % halogenated compounds. Furthermore, ammonia accounted for 7.9 % of the total detected gases, likely originating from nitrogen-containing compounds in hospital waste [57].

The analysis revealed that hydrocarbons constituted the highest proportion of emissions among the identified pollutants. The average concentrations of significant hydrocarbons were n-hexane (6354.8 µg/m^3), n-heptane (6009 µg/m^3), methylcyclopentane (3963.8 µg/m^3), n-octane (2733.2 µg/m^3), cyclohexane (2242.1 µg/m^3), and n-nonane (2148.3 µg/m^3). These findings align with the study by Yamashita et al. [61], which demonstrated that hydrocarbons could be released from plastic and rubber waste even at temperatures below 100 °C through thermal processes. Hydrocarbon emissions from infectious waste decontamination devices arise from various sources, including pharmaceutical residues containing hydrocarbon-based active ingredients or solvents, the thermal degradation of plastic packaging, and residual chemical disinfectants like alcohols (e.g., ethanol and isopropyl alcohol). These emissions are further amplified by low-temperature thermal processes and external contamination, such as spills of foreign materials [62,63].

The results presented in Fig. 5(A–D) indicate that oxygenated compounds play a significant role in pollutant emissions within the environment of sterilizer devices. Specifically, the average indoor air concentration of ethyl alcohol in sterilizer equipment areas reached an astonishing 7271.3 µg/m^3. Additionally, the average concentrations of ethyl acetate and butyl acetate were 6617.7 µg/m^3 and 4452.3 µg/m^3, respectively. These findings differ significantly from the results reported by Bessonneau et al. [59] in French

educational hospitals, where ethanol, at 928 ± 958 μg/m³, was the most abundant compound identified. This discrepancy is likely attributable to the extensive use of ethyl alcohol as an oxygenated solvent in various medical processes and procedures in hospitals. Oxygenated compounds are typically generated during the decomposition of organic materials in medical waste treatment processes, such as incineration, autoclaving, or chemical disinfection [64]. Infectious waste containing pharmaceuticals, biological tissues, and chemical residues may, under thermal treatment, be converted into oxygenated compounds such as alcohols, aldehydes, and acids. Additionally, in chemical disinfection processes, the use of agents such as sodium hypochlorite or peracetic acid can lead to the formation of oxygenated compounds as byproducts of reactions with organic materials in the waste stream [65,66]. The generation of oxygenated compounds in medical waste management raises environmental concerns, as some are VOCs that contribute to air pollution and pose risks to human health. As a result, strict regulations are in place to limit these emissions. To minimize the release of such pollutants, medical waste treatment facilities must adopt advanced technologies and management strategies while complying with legal requirements, protecting both the environment and healthcare personnel [67,68].

Air pollution measurements conducted after the operation of sterilizer devices revealed that dichloromethane, as a halogenated compound, exhibited the highest average concentration, reaching 8633 μg/m³. Additionally, other halogenated compounds, including vinyl chloride (3764 μg/m³), trichloroethylene (2489 μg/m³), and tetrachloroethylene (1710 μg/m³), were detected at significant levels. These findings align with previous studies estimating the chloride content in infectious waste to range between 0.42 % and 2.8 %. Furthermore, prior research on emissions from incineration systems consistently highlights the substantial contribution of halogenated compounds, particularly dichloromethane and vinyl chloride, due to their high volatility under elevated temperatures [26,69]. Although the sterilizer devices investigated in this study operate at lower temperatures compared to incinerators, the elevated levels of these compounds may stem from the presence of halogenated plastic polymers and the use of halogenated solvents or chemicals in the waste stream. This is corroborated by Karagiannidis et al. [70], who identified significant emissions of VOCs, notably 2-propanol and vinyl chloride, from sterilizer devices in 20 hospitals, with average concentrations of 4.33 mg/m³ and 2.6 mg/m³, respectively. In contrast, the current study recorded a substantially higher maximum concentration of vinyl chloride (7457 μg/m³) from the hydroclave system. The high levels of halogenated compounds detected in hospital sterilization environments emphasize the need for robust air pollution control measures and effective waste management strategies, including the efficient segregation of halogenated materials from healthcare waste to minimize their generation and release [22,26,71].

Among aromatic compounds, ethylbenzene exhibited the highest average concentration of 2629 μg/m³, followed by pyridine (2154 μg/m³), xylene (2069 μg/m³), benzene (2018 μg/m³), toluene (1777 μg/m³), and styrene (1324 μg/m³), respectively. The significant increase in aromatic compounds in the indoor air after the operation of shredder-equipped autoclaves (Hospital A), compared to the changes observed in other devices (based on pre- and post-operation measurements), is likely attributable to the shredding process and the release of pollutants under high temperature and pressure conditions. These findings suggest that the mechanical processes and operational conditions specific to this device have a more pronounced impact on the emission of aromatic compounds. Furthermore, the variable composition of input waste, particularly the proportion of plastics due to inconsistent segregation policies, may play a crucial role in this increase [7,21,68]. The analysis of BTEX concentrations in the indoor air of sterilizer devices (Fig. 5(A–D)) reveals that Hospital C, utilizing a hydroclave, exhibited the highest BTEX level at 14.02 mg/m³. This was followed by autoclaves with shredders at 9.13 mg/m³, autoclaves without shredders at 6.07 mg/m³, and dry heating systems at 4.76 mg/m³. In a similar study by Farzadkia et al. [23] conducted across four hospitals in Tehran, the maximum BTEX concentration was 2.29 mg/m³ for autoclaves with shredders, while the minimum was 0.242 mg/m³ for autoclaves without shredders. Their findings also indicated that dry heating and hydroclave ranked second and third, respectively, in BTEX concentration. The differences observed between this study and that of Farzadkia et al. [23] can be attributed not only to variations in the input waste but also to factors such as operational protocols, indoor ventilation, and the age of the devices. In a study conducted by Vilavert et al. [72] in Beijing, the concentration of BTEX compounds in the exhaust air of a waste incinerator was reported at 1240 μg/m³. The elevated levels of aromatic compounds observed in this study can be explained by the sources and processes associated with their release in infectious waste treatment. Pharmaceuticals, which often contain aromatic structures, are a significant contributor when disposed of in waste streams, especially if improperly segregated. Furthermore, the decomposition of organic materials in infectious waste, such as tissues and biological fluids, can result in the biochemical production of aromatic metabolites [25,26,30].

A comparative analysis of pollutant group distribution in indoor areas, before and after the operation of sterilizers, indicates a significant shift. Initially, oxygenated compounds had a higher share of total pollution concentration than other classes. However, during sterilizer operation and steam discharge, the proportion of hydrocarbon compounds increased, likely due to the inherent instability of hydrocarbons that react rapidly with hydroxyl (OH) radicals, resulting in their degradation. Conversely, oxygenated compounds are more stable and persist longer in the air. The notable presence of halogenated and aromatic compounds among indoor pollutants is critical due to their potential hazards. The elevated levels of these compounds require careful attention and thorough risk assessment due to increased health risks for healthcare workers and patients [21,72].

To evaluate the effect of atmospheric conditions and indoor ventilation on pollutant emissions, the correlation between pollutant concentrations and these factors was examined. The findings indicated a weak positive correlation between temperature and humidity with pollutant concentrations. Conversely, a significant negative correlation was observed between ventilation and pollutant levels. The negative ventilation system employed in the vicinity of the sterilization devices proved to be minimally effective. While atmospheric conditions did have some influence on the average pollutant concentrations, their impact was relatively minor. Instead, the composition of the waste fed into the device and its operational settings were identified as more critical determinants of pollutant emissions. The elevated emission levels from these sterilization devices present serious health risks, not only to employees and patients but also to the surrounding community and the environment, highlighting the urgent need for enhanced control measures and mitigation strategies [22,64].

The results of this study carried important practical implications for both hospital waste management practices and the design of sterilization devices. Optimizing sterilizer design, particularly by enhancing steam penetration and ensuring uniform sterilization conditions, can significantly improve the efficiency of waste treatment. Furthermore, the implementation of stringent operational monitoring, focusing on temperature, is essential to ensure consistent and effective sterilization outcomes. The findings also highlighted the necessity for advanced air pollution control systems within sterilization areas to minimize the risks associated with airborne pollutants. Moreover, devices designed to reduce emissions—such as autoclaves equipped with shredders—demonstrated considerable environmental and health benefits. These insights provided valuable guidance for policymakers and healthcare planners, supporting informed decisions regarding the selection of sterilization technologies that not only reduce pollutant emissions but also enhance operational safety and foster environmental sustainability within healthcare environments.

This study faced several limitations. First, due to time and resource constraints, only a limited number of hospitals and device types were included. Furthermore, environmental factors such as ventilation rates and temperature fluctuations may have affected pollutant concentration measurements, potentially introducing variability in the results. These factors, while recorded during the study, may influence comparisons between devices and need to be considered in interpreting the findings.

4. Conclusion

The findings of this study provide critical insights into the performance and environmental implications of hospital waste management practices and sterilizer devices. While the total waste generated in the surveyed hospitals aligned with the typical range observed in healthcare settings, deficiencies in waste management—particularly in waste minimization and inadequate segregation—significantly increased the proportion of infectious waste relative to total waste. Among the four sterilizer devices evaluated, the autoclave with an internal shredder exhibited the highest decontamination efficiency, while the autoclave without shredder demonstrated the least effectiveness. Among the mechanical monitoring parameters of sterilizer devices, only temperature compliance exhibited a significant relationship with biological outcomes for both vials and microbial cultures. Significant differences in VOC and ammonia emissions were observed among the devices, with the hydroclave producing the highest levels of emissions (134.51 mg/m^3), compared to the autoclave with shredder (49.13 mg/m^3), autoclave without shredder (58.97 mg/m^3), and the dry heat device (55.35 mg/m^3). This study demonstrated that mechanical monitoring parameters, particularly temperature, combined with microbial assessments, offer a reliable framework for evaluating decontamination efficiency of sterilizer devices. These findings emphasize the need for a holistic approach to the selection and operation of sterilizer devices, prioritizing not only decontamination performance but also equipping the devices with advanced air pollution control technologies.

CRediT authorship contribution statement

Zohreh Mousavi: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Reza Saeedi:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Mohsen Saadani:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Monireh Majlesi:** Visualization, Validation, Methodology, Conceptualization. **Tina Tajalli Tehrani:** Writing – original draft, Software. **Mehrnoosh Abtahi:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Data availability statement

Data will be made available on request. For requesting data, please write to the corresponding author.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Mehrnoosh Abtahi reports financial support was provided by Shahid Beheshti University of Medical Sciences School of Public Health and Safety. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Sadeghi, A. Fadaei, M. Ataee, Assessment of hospitals medical waste management in Chaharmahal and Bakhtiari Province in Iran, Archives of Agriculture and Environmental Science 5 (2) (2020) 157–163.
[2] Y. Wei, M. Cui, Z. Ye, Q. Guo, Environmental challenges from the increasing medical waste since SARS outbreak, J. Clean. Prod. 291 (2021) 125246.
[3] J.S. Tabrizi, R. Rezapour, M. Saadati, S. Seifi, B. Amini, F. Varmazyar, Medical waste management in community health centers, Iran. J. Public Health 47 (2) (2018) 286.

[4] n Abedinzadeh, f Abedinzadeh, t Abedi, Study of strategic factors of rasht city solid waste management by SWOT method and QSPM matrix formation, J. Environ. Stud. 37 (57) (2011) 1–12.
[5] A. Rastegar, H. Gholami, Survey of solid waste management in small and large selected hospitals of Tehran, Journal of Ilam University of Medical Sciences 22 (2) (2014) 149–157.
[6] A. Ferdowsi, M. Ferdowsi, M.J. Mehrani, Health-care waste management status in Iran (case study of Gachsaran County, 2012–2013), Int. J. Environ. Health Eng. 5 (1) (2016) 21.
[7] M. Ali, W. Wang, N. Chaudhry, Y. Geng, Hospital waste management in developing countries: a mini review, Waste Manag. Res. 35 (6) (2017) 581–592.
[8] J. Wang, J. Shen, D. Ye, X. Yan, Y. Zhang, W. Yang, et al., Disinfection technology of hospital wastes and wastewater: suggestions for disinfection strategy during coronavirus Disease 2019 (COVID-19) pandemic in China, Environ. Pollut. 262 (2020) 114665.
[9] S. Sharma, A. Chauhan, A. Ranjan, D.M. Mathkor, S. Haque, S. Ramniwas, et al., Emerging challenges in antimicrobial resistance: implications for pathogenic microorganisms, novel antibiotics, and their impact on sustainability, Front. Microbiol. 15 (2024) 1403168.
[10] K. Kojima, B. Allan, A. Beswick, M. Heisz, P. Hoffman, S. Karlen, et al., Decontamination and Waste Management, 2020.
[11] M. Farzadkia, S. Golbaz, Sajadi HsjjoH, Surveying hospital waste management in karaj in the year of 2013, Journal of Hospital 14 (1) (2015) 105–115.
[12] S. Pandey, B.R. Divekar, S. Gupta, Bio-medical waste mangement–a review of practices adopted by hospitals in Pune city, Indian J. Forensic Community Med. 3 (2) (2016) 110–120.
[13] H.G. Mazzei, S. Specchia, Latest insights on technologies for the treatment of solid medical waste: a review, J. Environ. Chem. Eng. 11 (2) (2023) 109309.
[14] A. Eslami, P. Nowrouz, S. Sheikholeslami, Status and challenges of medical waste management in hospitals of Iran, Civil Engineering Journal 3 (9) (2017) 741–748.
[15] O. Maamari, L. Mouaffak, R. Kamel, C. Brandam, R. Lteif, D. Salameh, Comparison of steam sterilization conditions efficiency in the treatment of Infectious Health Care Waste, Waste Manag. 49 (2016) 462–468.
[16] G. Giakoumakis, D. Politi, D. Sidiras, Medical waste treatment technologies for energy, fuels, and materials production: a review, Energies 14 (23) (2021) 8065.
[17] B.A. Khan, L. Cheng, A.A. Khan, H. Ahmed, Healthcare waste management in Asian developing countries: a mini review, Waste Manag. Res. 37 (9) (2019) 863–875.
[18] Z. Yousefi, M. Avak Rostami, Quantitative and qualitative characteristics of hospital waste in the city of Behshahr-2016, Environmental Health Engineering and Management Journal 4 (1) (2017) 59–64.
[19] M. Fahiminia, E. Taherian, M. Khazaei, N. Paidari Shayesteh, S. Arsang Jang, Monitoring, verification, and treatment of infectious wastes and their optimal management in the hospitals of qom city, Iran, Qom Univ. Med. Sci. J. 10 (6) (2016) 75–84.
[20] C. Yaman, Application of sterilization process for inactivation of bacillus stearothermophilus in biomedical waste and associated greenhouse gas emissions, Appl. Sci. 10 (15) (2020) 5056.
[21] Y.-S. Park, M.-J. Kim, Y.-S. Yoon, T.-W. Jeon, H.-H. Choi, A study of the effect of testing for diversification of healthcare waste sterilization and crushing facilities, Heliyon 10 (11) (2024) e31962.
[22] Z.Z. Al-Saedi, S.M. Taib, Ecological impacts, management and disposal methods for medical wastes: a review, Journal of Ecological Engineering 25 (7) (2024) 25–40.
[23] M. Farzadkia, H. Gholami, A. Esrafili, A. Farshad, M.J.I.O.H. Kermani, Study of the volatile organic compounds (VOCs) in the exhaust air from low heat sterilizer devices of four hospitals in Tehran, Iran. Occup. Health 11 (1) (2014) 10.
[24] M. Anjum, H. Min, Z. Ahmed, Healthcare waste management through multi-stage decision-making for sustainability enhancement, Sustainability 16 (11) (2024) 4872.
[25] Content and formation cause of VOCs in medical waste non-incineration treatment Project, in: J. Dengchao, T. Hongjun, B. Zhenbo, L. Yang (Eds.), IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2018.
[26] J. Hadar, T. Tirosh, O. Grafstein, E. Korabelnikov, Autoclave emissions—hazardous or not, Journal of the American Biological Safety Association 2 (3) (1997) 44–51.
[27] A. Rafiee, J.M. Delgado-Saborit, E. Gordi, B. Quémerais, V.K. Moghadam, W. Lu, et al., Use of urinary biomarkers to characterize occupational exposure to BTEX in healthcare waste autoclave operators, Sci. Total Environ. 631 (2018) 857–865.
[28] M. Attrah, A. Elmanadely, D. Akter, E.R. Rene, A review on medical waste management: treatment, recycling, and disposal options, Environments 9 (11) (2022) 146.
[29] P.A. Reinhardt, Infectious and Medical Waste Management, CRC Press, Boca Raton, 2018.
[30] M.N. Akhtar, S. Riaz, N. Ahmad, E. Jaseer, Pioneering aromatic generation from plastic waste via catalytic thermolysis: a minireview, Energy Fuel 38 (13) (2024) 11363–11390.
[31] M. Rafiee, M. Abtahi, A. Hajihosseinlo, Performance evaluation of infectious wastes decontamination devices in general hospitals under the auspicious of Khoy University of Medical Sciences in 2020, Journal of Health in the Field 9 (3) (2021).
[32] A. Fadaei, Comparison of medical waste management methods in different countries: a systematic review, Rev. Environ. Health 38 (2) (2023) 339–348.
[33] J. Torkashvand, H. Pasalari, A. Jonidi-Jafari, M. Kermani, O. Nasri, M. Farzadkia, Medical waste management in Iran and comparison with neighbouring countries, Int. J. Environ. Anal. Chem. 102 (12) (2022) 2805–2818.
[34] A.N. Zaki, J.R. Campbell, Infectious waste management and laboratory design criteria, Am. Ind. Hyg. Assoc. J. 58 (11) (1997) 800–808.
[35] A. Mohseni Band-pay, M. Majlessi, M. Tabrizi Azad, Performance evaluation of non-incineration treatment facilities for disinfection of medical infectious and sharps wastes in educational hospitals of Shahid Beheshti University of Medical Sciences in 2013, Environmental Health Engineering and Management Journal 2 (2) (2015) 93–97.
[36] Y. Liu, Y. Liu, H. Yang, Q. Wang, F. Cheng, W. Lu, et al., Occupational health risk assessment of BTEX in municipal solid waste landfill based on external and internal exposure, J. Environ. Manag. 305 (2022) 114348.
[37] N. Singh, O.A. Ogunseitan, Y. Tang, Medical waste: current challenges and future opportunities for sustainable management, Crit. Rev. Environ. Sci. Technol. 52 (11) (2022) 2000–2022.
[38] J.M. Chisholm, R. Zamani, A.M. Negm, N. Said, M.M. Abdel daiem, M. Dibaj, et al., Sustainable waste management of medical waste in African developing countries: a narrative review, Waste Manag. Res. 39 (9) (2021) 1149–1163.
[39] E. Cook, A. Woolridge, P. Stapp, S. Edmondson, C.A. Velis, Medical and healthcare waste generation, storage, treatment and disposal: a systematic scoping review of risks to occupational and public health, Crit. Rev. Environ. Sci. Technol. 53 (15) (2023) 1452–1477.
[40] M. Minoglou, S. Gerassimidou, D. Komilis, Healthcare waste generation worldwide and its dependence on socio-economic and environmental factors, Sustainability 9 (2) (2017) 220.
[41] A. Tavakkolian, A. Ebrahimi, H. Pourzemani, G. Yadegarfar, A survey on medical solid waste management in hospitals in Bushehr province, Iran, in years 2015-2016, Health System Research 14 (1) (2018) 48–55.
[42] M. Sartaj, R. Arabgol, Assessment of healthcare waste management practices and associated problems in Isfahan Province (Iran), J. Mater. Cycles Waste Manag. 17 (1) (2015) 99–106.
[43] N. Bayat, M. Alimohammadi, R. Nodehi, M. Dehghani, K. Yaghmaeian, M. Berahmand, A Survey on the status of hospital waste management using Individualized rapid assessment tool unique (I-RAT), J Res Environ Health 1 (3) (2015) 217–227.
[44] E. Bazrafshan, K. Afsari, N. Pormolaee, M. Forghani, H. Khedengi, H. Kord Mostafapor, Survey of dental solid waste management in Sistan and Baluchestan Province, Journal of Sabzevar University of Medical Sciences 22 (1) (2015) 73–83.
[45] B.-K. Lee, M.J. Ellenbecker, R. Moure-Ersaso, Alternatives for treatment and disposal cost reduction of regulated medical wastes, Waste Manag. 24 (2) (2004) 143–151.
[46] M.A. Ferraz, J.B. Cardoso, S.R. Pontes, Concentration of atmospheric pollutants in the gaseous emissions of medical waste incinerators, J. Air Waste Manag. Assoc. 50 (1) (2000) 131–136.

[47] M.K. Manar, K.K. Sahu, S.K. Singh, Hospital waste management in nonteaching hospitals of lucknow city, India, J. Fam. Med. Prim. Care 3 (4) (2014) 393.
[48] H.-J. Zhang, Y.-H. Zhang, Y. Wang, Y.-H. Yang, J. Zhang, Y.-L. Wang, et al., Investigation of medical waste management in Gansu Province, China, Waste Manag. Res. 31 (6) (2013) 655–659.
[49] M.T. Ebrahimi, A. Jafarpour, S. Kamgoo, S. Aghamiri, A.B. Kazemi, R. Vahidi-Kolur, et al., Quantitative and qualitative assessment of waste produced in sari hospitals, Int. J. Environ. Health Eng. 10 (1) (2021) 1.
[50] E. Kousha, B. Sepehrnia, A. Bidgolian, Survey quantity and quality of solid waste in health-care centers in south of tehran, Environment and Interdisciplinary Development 6 (71) (2021) 1–10.
[51] R.M. Zulqarnain, H. Naveed, S. Askar, M. Deveci, I. Siddique, O. Castillo, Assessment of bio-medical waste disposal techniques using interval-valued q-rung orthopair fuzzy soft set based EDAS method, Artif. Intell. Rev. 57 (8) (2024) 210.
[52] A. Farshad, H. Gholami, M. Farzadkia, R. Mirkazemi, M. Kermani, The safety of non-incineration waste disposal devices in four hospitals of Tehran, Int. J. Occup. Environ. Health 20 (3) (2014) 258–263.
[53] M. Malakootian, M. Sadeghi, S. Dowlatshahi, Evaluation function of non-hazardous non-incineration waste devices in kerman and sirjan hospitals in the year 2013, Journal of Hospital 14 (1) (2015) 77–84.
[54] M. Dursun, E.E. Karsak, M.A. Karadayi, Assessment of health-care waste treatment alternatives using fuzzy multi-criteria decision making approaches, Resour. Conserv. Recycl. 57 (2011) 98–107.
[55] I. Salkin, Conventional and alternative technologies for the treatment of infectious waste, J. Mater. Cycles Waste Manag. 5 (1) (2003) 9–12.
[56] M. Miranzadeh, M. Sabahi Bidgoli, A. Zarfeshani, M. Heidari, Study on performance of infectious waste sterilizing set in kashan Shahid Beheshti hospital and determination of its optimum operating condition, Iran. J. Health Environ. 4 (4) (2012) 493–506.
[57] M.F. Hassan, Z. Shareefdeen, Recent developments in sustainable management of healthcare waste and treatment technologies, Journal of Sustainable Development of Energy, Water and Environment Systems 10 (2) (2022) 1–21.
[58] N. Gupta, N.S. Abd El-Gawaad, L.O. Mallasiy, Hospital-borne hazardous air pollutants and air cleaning strategies amid the surge of SARS-CoV-2 new variants, Heliyon 10 (20) (2024) e38874.
[59] V. Bessonneau, L. Mosqueron, A. Berrubé, G. Mukensturm, S. Buffet-Bataillon, J.-P. Gangneux, et al., VOC contamination in hospital, from stationary sampling of a large panel of compounds, in view of healthcare workers and patients exposure assessment, PLoS One 8 (2) (2013) e55535.
[60] F. Ostadi, F. Mortezazadeh, F. Gholami-Borujeni, Comparing and prioritizing different methods of collection and decontamination of waste in decentralized healthcare centers, Journal of Advances in Environmental Health Research 9 (4) (2021) 277–284.
[61] K. Yamashita, N. Yamamoto, A. Mizukoshi, M. Noguchi, Y. Ni, Y. Yanagisawa, Compositions of volatile organic compounds emitted from melted virgin and waste plastic pellets, J. Air Waste Manag. Assoc. 59 (3) (2009) 273–278.
[62] UNEP, Compendium of technologies for treatment/destruction of healthcare waste, in: Division of Technology IaE, Japan United Nations Environment Programme, Osaka, 2012.
[63] T. Zikhathile, H. Atagana, J. Bwapwa, D. Sawtell, A review of the impact that healthcare risk waste treatment technologies have on the environment, Int. J. Environ. Res. Publ. Health 19 (19) (2022) 11967.
[64] Y. Chartier, Safe Management of Wastes from Health-Care Activities, World Health Organization, 2014.
[65] E. Papadimitriou, Hydrolysis of organic matter during autoclaving of commingled household waste, Waste Manag. 30 (4) (2010) 572–582.
[66] S. Koda, S. Kumagai, H. Ohara, Environmental monitoring and assessment of short-term exposures to hazardous chemicals of a sterilization process in hospital working environments, Acta Med. Okayama 53 (5) (1999) 217–223.
[67] B. Bharti, H. Li, Z. Ren, R. Zhu, Z. Zhu, Recent advances in sterilization and disinfection technology: a review, Chemosphere 308 (2022) 136404.
[68] Q.G. Omo, N.E. Hassan, Biomedical waste management and their effects on the Environment: a review, World Journal of Advanced Engineering Technology and Sciences 11 (1) (2024) 86–95.
[69] M. Jang, H. Yang, S.-A. Park, H.K. Sung, J.M. Koo, S.Y. Hwang, et al., Analysis of volatile organic compounds produced during incineration of non-degradable and biodegradable plastics, Chemosphere 303 (2022) 134946.
[70] A. Karagiannidis, A. Papageorgiou, G. Perkoulidis, G. Sanida, P. Samaras, A multi-criteria assessment of scenarios on thermal processing of infectious hospital wastes: a case study for Central Macedonia, Waste Manag. 30 (2) (2010) 251–262.
[71] J. Chruściel, M. Kudzin, D. Piwowarska, N. Festinger, Risks Associated with the Presence of PVC in the Environment and Methods of its Elimination, 2023.
[72] L. Vilavert, M. Nadal, I. Inza, M.J. Figueras, J.L. Domingo, Baseline levels of bioaerosols and volatile organic compounds around a municipal waste incinerator prior to the construction of a mechanical-biological treatment plant, Waste Manag. 29 (9) (2009) 2454–2461.