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Research article

A study of the effect of testing for diversification of healthcare waste sterilization and crushing facilities

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ABSTRACT

This study conducted sterilization testing under different conditions using different strains for sterilization and crushing, the intermediate healthcare waste treatment phase, and proposed strategies for diversifying corresponding facilities in addition to promoting their installation. Five indicator microorganisms were selected to test the sterilization efficiency of steam, microwave, and chemical methods. Steam sterilization testing was conducted in accordance with legal and technological standards, microwave testing was carried out according to the legal standard, and chemical sterilization employed three typical compounds. Steam and microwave sterilization achieved 99.9999 % inactivation rates for all five strains under both conditions used; whereas under the chemical sterilization analyses, sodium hypochlorite (1000 ppm) failed to meet the inactivation requirement of the fungal strain *Candida albicans*, requiring further investigation. Based on these findings, this study presents strategies for diversifying sterilization·crushing facilities and promoting their installation.

1. Introduction

In Korea, healthcare waste was previously managed by the Ministry of Health and Welfare under the Medical Service Act; however, in August 2000, this responsibility was transferred to the Ministry of Environment, where it has been treated as infectious waste under the Wastes Control Act. The Enforcement Decree of the Wastes Control Act was amended in August 2004 to designate additional types of waste-discharging businesses, resulting in a total of 15 types of correlated healthcare facilities. Due to the infectious nature of healthcare waste, it is disposed of and treated in exclusive containers, vehicles, and incineration facilities. Furthermore, it is subject to strict monitoring and control by the Radio Frequency Identification (RFID) management system operated by the Korea Environment Corporation [1]. Further, the amount of healthcare waste in Korea has been growing steadily due to the country's aging population and expansion of healthcare services [2], increasing by 17 % from 200,000 t in 2015 to 234,000 t in 2019 [3]. Given the current rate of increase, healthcare waste is expected to continue to rise in the future [2].

To address some of these issues, relevant laws and regulations have been made less stringent. Firstly, disposable diapers are no longer categorized as healthcare waste. Previously, all disposable diapers utilized by patients, whether afflicted with communicable or non-communicable diseases, in healthcare facilities were considered healthcare waste, and disposed of through separate incineration

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procedures. Following the amendment, disposable diapers discharged from patients with non-communicable diseases were incinerated with other general waste items, leading to a decrease in healthcare waste volume [4]. Secondly, the restrictions on waste treatment facilities, namely sterilization·crushing facilities, near school zones have been eased, as their installation was previously prohibited within 200 m of school premises [5,6]. Thirdly, under special circumstances, healthcare waste was more recently allowed to be treated at designated waste incinerators. Since it can be infectious, this waste must be disposed of and treated in a specialized healthcare waste incinerator. However, in the face of the imminent depletion of the capacity of dedicated healthcare waste incinerators, the relevant provision was amended to allow healthcare waste with low pollution risk for both environment and human health to be treated at designated waste treatment facilities in emergency situations [7].

Accordingly, even though laws and regulations have become less stringent to better stabilize healthcare waste treatment, problems persist. First, the processing capacity of healthcare waste incinerators is limited. Currently, healthcare waste is incinerated separately at designated facilities, of which there are 13 across Korea as of 2020 [8]; yet, their processing capacity falls short of the total healthcare waste generated, and expanding or constructing new facilities is challenging due to strong opposition from residents and

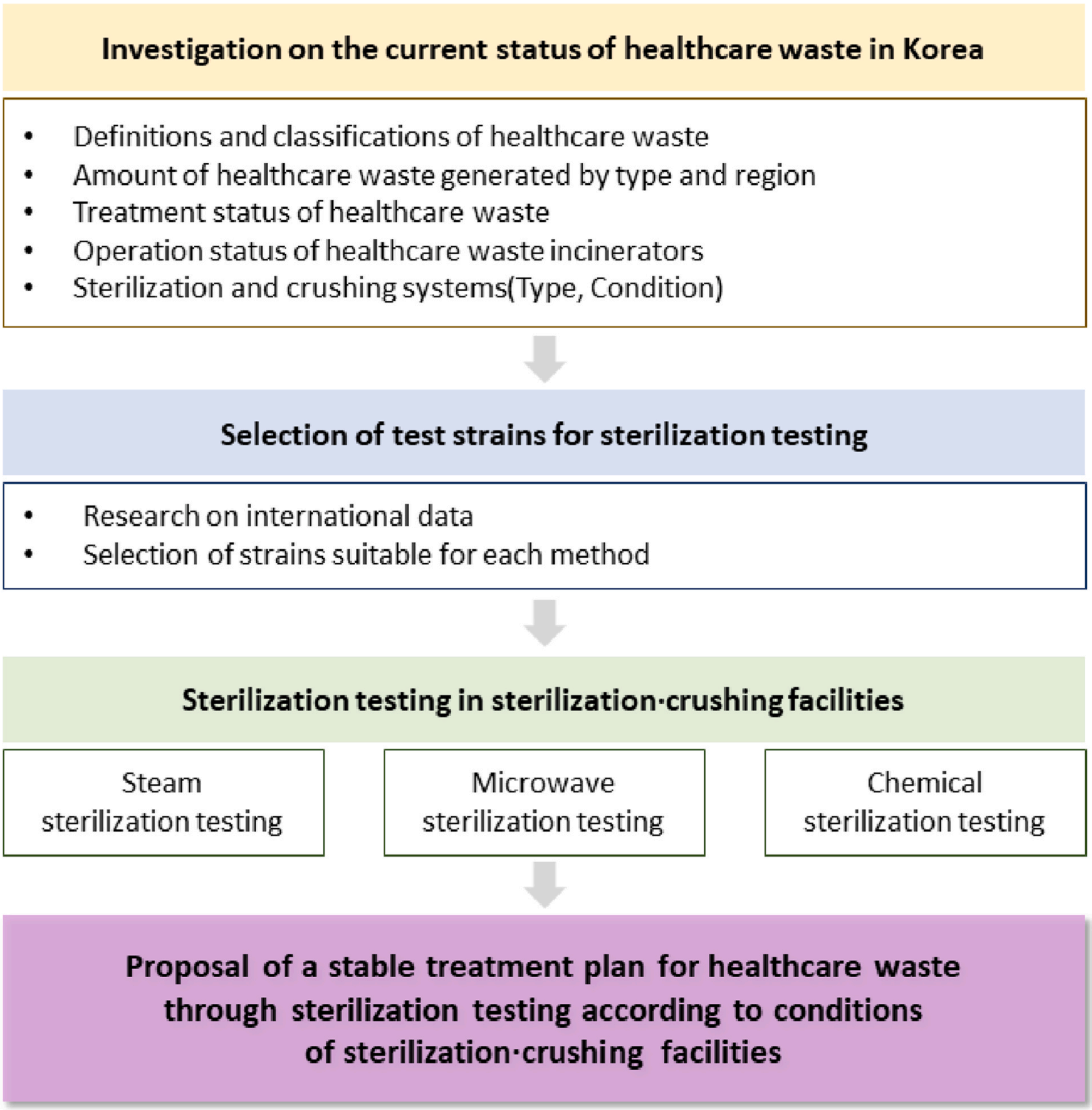

Fig. 1. Research Framework used in this study.

local governments [9]. Second, as the amount of healthcare waste increases, the processing unit price also rises, leading to an increase in cases of illegal storage and negligence to avoid the financial burden of processing costs at healthcare and intermediate disposal facilities. Third, while 54 % of Korea's total healthcare waste is generated in the Seoul Capital Area [8], there are only three healthcare waste incinerators serving this region. In addition, healthcare waste incinerators are not evenly distributed throughout the country, which increases the potential risk of accidents during long-distance transportation [10]. The fourth issue surrounds Korea's limited healthcare waste intermediate treatment options. The World Health Organization (WHO) and Basel Convention, as well as countries such as the United States, Japan, and the UK have proposed various healthcare waste intermediate treatment methods, including thermal (steam, dry heat, microwave) and chemical treatments; however, Korea only allows thermal methods, while the related environmental conditions, such as temperature, exposure time, and pressure are subject to stricter standards and regulations compared to other countries [11]. Fifth, Korea's healthcare waste sterilization testing conditions are extremely stringent. While some countries still specify indicator microorganisms for sterilization testing, they recognize sterilization capacity if an equivalent effect is achieved to satisfy sterilization efficacy corresponding to Level III microbial inactivation of healthcare waste recommended by the State and Territorial Association on Alternative Treatment Technologies (STAATT) in USA. Presently in Korea, only spore strains are allowed for sterilization testing, while all tests using other strains are not recognized [11]. To address these problems, a stable treatment alternative is being considered, which involves final treatment of healthcare waste in a general incinerator following intermediate sterilization and crushing treatment at large general hospitals [12,13].

These sterilization and crushing treatment can process some healthcare waste in accordance with the Waste Control Act. The types that can be treated include Pathological waste, Sharp waste, General medical waste which is low risk of infection. On the other hand, radioactive waste generated from Nuclear Medicine departments of hospitals. These radioactive waste should be managed and treated individually because these waste are dangerous. Currently, they are subjected to other law, directive and decrees by collaborating with Korea Radioactive Waste Agency. Therefore, this study has been carried out by excluding this theme.

Therefore, this study was conducted to explore the feasibility of diversifying healthcare waste sterilization and crushing facilities by performing sterilization testing using different sterilization·crushing systems and a variety of indicator microorganisms. Further, the potential hazards associated with additional installations of healthcare waste treatment facilities were examined, and strategies to counter such hazards were proposed. To achieve these objectives, the current healthcare waste generation and treatment status in Korea was inspected. The microbial inactivation efficiency of different healthcare waste treatment methods on five microorganisms (including spores, as per the Korean legal standard) which belong to Group III of the WHO classification was assessed, while the possibility of diversifying the installation of sterilization and crushing facilities was explored. Lastly, sterilization testing for steam sterilization·crushing, microwave sterilization·crushing, and chemical treatment facilities was conducted, and stable healthcare waste treatment strategies were proposed which can be implemented independently in healthcare facilities using their own sterilization and crushing equipment.

2. Materials and methods

The proposed research approach method for stable treatment plan for healthcare waste consists of three stages. In the first stage, it is necessary to investigate the current status of healthcare waste in Korea. In the second stage, strain selection was necessary for sterilization testing. For this purpose, data were investigated and strains suitable for each method were selected. Finally, sterilization testing were performed under three conditions. The framework of this research is shown in Fig. 1.

2.1. Current status of healthcare waste in Korea

The data on healthcare waste generation and processing were extracted from the national statistics portal operated by Statistics Korea, and the Allbaro system operated by the Korea Environment Corporation, the latter of which is a nationwide real-time electronic waste management system that tracks the generation, transportation, treatment, and disposal of hazardous waste, including healthcare waste. To review status of healthcare waste, research institute reports, related papers, and press releases were consulted. In addition, field research at healthcare waste dischargers and designated incinerators, as well as individual interviews were conducted. Lastly, meetings with relevant experts from the government, industry, and academia were held to gain a deeper understanding of the issues and discuss potential solutions.

2.2. Testing of sterilization and crushing facilities

To gather data related to sterilization·crushing facilities and microbial sterilization effects, data provided by the WHO and STAATT were reviewed. Korean sterilization and crushing sites currently were also visited, while interviews and meetings with relevant experts were conducted. Additional data were collected through literature reviews and online research.

Steam sterilization·crushing facility is not currently being operated in Korea (as of 2020); therefore, correlated testing was performed in a large high-pressure steam sterilizer owned by Korea Environment Corporation. First, two environmental conditions (time, temperature) of the high-pressure steam sterilizer were established. The first is the current legal conditions. Currently, the Wastes Control Act stipulates that the performance maintenance condition for steam sterilization·crushing facility is 30 min at 121 °C. Therefore, the first condition was set at 121 °C for 30 min to ensure that this legal standard. The second conditions for technological development. This assumes that steam sterilization·crushing facility, which has developed technology in Koreas or other countries, in the future. As of 2020, the sterilization·crushing facility being prepared for introduction in Korea is facility with a capacity of 138 °C for

10 min. However, it is not being introduced due to Korean regulations. Therefore, we set the conditions of the high-pressure steam sterilizer of M company 2000 series from Spain currently located at the Korea Environment Corporation to 138 °C for 10 min and then attempted to determine the sterilization efficiency. However, in the case of this high-pressure steam sterilizer, the maximum temperature only reached 134°. Therefore, the second conditions was set to 134° for 10 min. Next, two conditions for inserting the indicator vial were set. The first is basic treatment. In this case, the indicator vial containing microorganisms was placed in an high-pressure steam sterilizer. The second is non-crushing treatment. This assumes that some healthcare waste is not crushed in an actual sterilization·crushing facility. For this purpose, the indicator vial was wrapped with a bandage and diaper and placed in an high-pressure steam sterilizer.

As of 2020, microwave sterilization·crushing(S company from USA) is currently used in large general hospitals within Korea for healthcare waste treatment. To test sterilization efficacy, microwave temperature and timing were set in accordance with the current legal standard, ≥95 °C for ≥30 min. The same five standard strains of microorganisms were used for the microwave sterilization·crushing analyses. Here, only a basic treatment was performed, as non-crushing treatment (which involves wrapping biological indicators with bandages or diapers) could not be performed provided that microwave sterilization·crushing in Korean hospitals involves steps of crushing, microwave irradiation, and sterilization.

Presently, only thermal methods, such as steam, dry heat, and microwaves, are allowed for intermediate healthcare waste treatment under the relevant laws in Korea. Chemical treatment, on the other hand, remains prohibited in Korea, although it is allowed in many other countries, and numerous chemical treatment devices are being manufactured [14]. In accordance with this international trend, there is a growing movement in Korea to improve the regulation of related laws through civil petitions. Therefore, this study aimed to test the safety of chemical sterilization, assuming that federal chemical health waste treatments will be introduced in the near future. Since no chemical sterilization·crushing treatment is available in Korea, testing was performed using chemical agents selected from among those typically used for disinfection, and applicable to onsite health waste treatment as specified by the Korean Disease Control and Prevention Agency [15]. Three chemical agents selected for each sterilization type: peracetic acid, glutaraldehyde, and sodium hypochlorite. Fig. 2 presents the treatment procedure for each sterilization type (see Fig. 3).

3. Results and discussion

3.1. Korea's healthcare waste status

3.1.1. Definitions and classifications of healthcare waste

In Korea, waste is managed according to the Wastes Control Act, and is largely divided into two categories: domestic waste and industrial waste. The former refers to non-industrial waste; whereas the latter refers to waste discharged from regulated places of business and other designated discharge locations. Specifically, healthcare waste is designated as industrial waste and is managed accordingly [7,11]. In the past, healthcare waste in Korea was managed under the name of 'extracts' by the Ministry of Health and Welfare, which were subject to specific regulations on processing, storage, transportation, and treatment, while related matters, such as the designation of extracts treatment and other management entities were regulated by law; however, in August 2000, the management of extracts was transferred to the waste management law system operated by the Ministry of Environment [1]. The Wastes Control Act refers to 'medical wastes' as those that may cause harm to human bodies via infection or otherwise, among the wastes discharged from public health and medical institutions, veterinary clinics, testing and inspection institutions, or other similar institutions. They are largely divided into three categories: infectious, hazardous, and general healthcare wastes. Hazardous healthcare waste is further divided into five subtypes: tissue waste, pathological waste, sharp waste, biochemical waste, and Blood-contaminated waste, forming the seven types of healthcare waste managed in Korea [7].

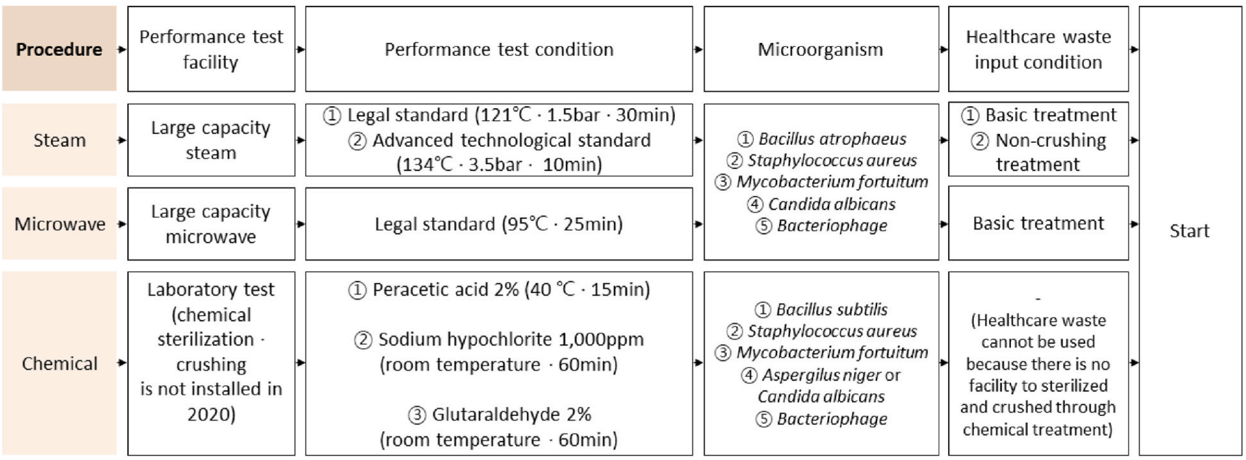

Fig. 2. Treatment procedure for each sterilization type.

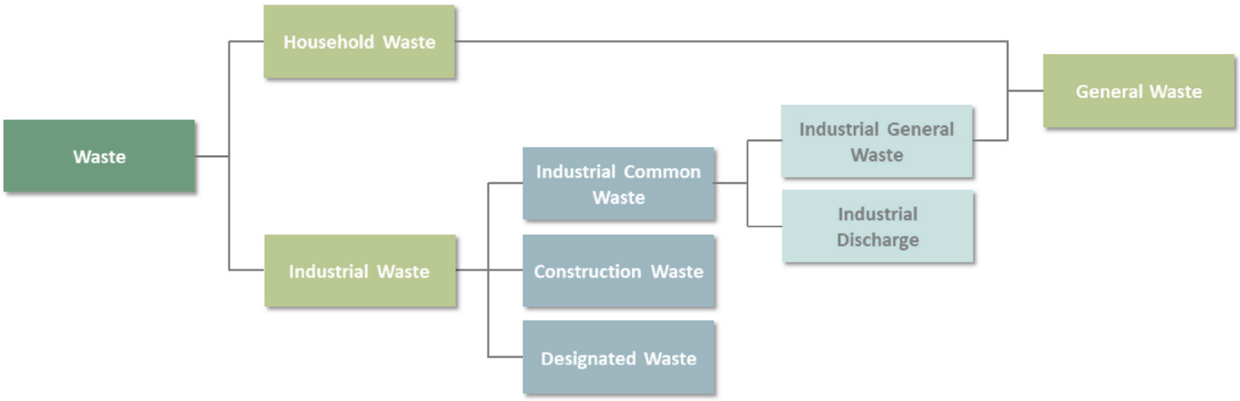

Fig. 3. Legal classification of waste in Korea.

3.1.2. Healthcare waste generation and treatment status

Among hazardous healthcare waste, although placentas technically correspond to tissue waste, it is recycled as an exception among healthcare waste items; accordingly, the current statistics for healthcare waste generation is established for a total of eight types of healthcare waste. The statistics regarding these eight types of healthcare waste showed that healthcare waste has been steadily increasing since 2016, with the lone exception of 2020, in which the total amount of health waste decreased by 17.14 % from 235,754 tons in 2019 to 195,351 tons in 2020 [8]. Notably, this decrease was associated with the COVID-19 pandemic, which led to a significant decrease in the number people visiting hospitals, resulting in drastically reduced overall volumes of healthcare waste. Additionally, in October 2019, disposable diapers for patients with non-communicable diseases were excluded from the healthcare waste classification system, further reducing the total volume of healthcare waste [16]. General healthcare waste comprised the largest portion from 2017 to 2021 (Table 1), accounting for >60 % of total healthcare waste. Specifically, general healthcare waste includes absorbent cotton, bandages, gauze, disposable diapers, sanitary napkins, disposable syringes, and infusion sets containing blood, body fluid, secretions, and excreta. Blood-contaminated waste, infectious medical waste, and pathological waste are other common types of healthcare waste. Table 1 presents the statistics for healthcare waste generation by year and by waste type.

An analysis of the volume of healthcare waste generated by region in Korea over the five-year period from 2017 to 2021 was also conducted by dividing the country into the Seoul Capital Area (SCA) and the non-SCA region. The overall mean proportions of healthcare waste generated in the SCA and non-SCA regions were 50 % and 49 %. The majority of the Korean population is concentrated in the SCA (50.2 % in 2020), which includes Seoul, Incheon, and Gyeonggi [17]. There, a high population density is associated with a high aging rate of the population, and increased medical services [18,19], explaining the relatively higher volume of healthcare waste generated in the SCA.

In Korea, healthcare waste is regulated by law to be treated either on-site in the discharging place of business or via an outsourced waste treatment company. Of these two healthcare waste treatment modalities classified by treatment entity, self-disposal involves incineration and other comparable methods; whereas outsourced treatment involves incineration, sterilization, and recycling. Regardless of the chosen treatment method, healthcare waste should be disposed of in a designated incineration or sterilization·crushing facility. Incineration is prescribed for healthcare wastes that contain potentially leaky substances, such as infectious waste, tissue waste, biochemical waste, blood, body fluid, and secretions, as well as healthcare wastes disposed of by intermediate or final waste disposal companies. Other healthcare wastes may be incinerated or sterilized, depending on their character and composition.

As the volume of healthcare waste increases, so too does the treatment volume. Healthcare waste treatment is divided into self-processing and outsourcing, with treatment methods largely divided into incineration, sterilization·crushing, recycling, and other

Table 1
Korea healthcare waste generation by type between 2017 and 2021 (unit: t·yr^{-1}).

Category	Number of wastes by year				
	2017	2018	2019	2020	2021
General medical waste	160,678	173,922	177,755	129,229	130,431
Infectious medical waste	2444	3972	4891	14,281	33,322
Tissue waste	8123	8932	7848	9625	9034
Pathological waste	11,992	12,973	11,133	13,795	15,304
Sharp waste	4700	5202	2738	5380	5409
Biochemical waste	5034	6226	5658	6413	6748
Blood-contaminated waste	26,014	27,016	25,733	16,600	17,638
Placenta	28	31	0	29	27
Total	219,013	238,272	235,754	195,351	217,915

methods. Among these four treatment techniques, incineration is most widely practiced, increasing from 92.9 % in 2017 to 97.2 % in 2021. Comparatively, 'others' (e.g., wastewater treatment) decreased from 6.8 % in 2017 to 1.7 % in 2021, while sterilization increased from 0.5 % in 2017 to 1.0 % in 2021 due to the installation of two sterilization·crushing facilities across the country. Recycling is the least frequent healthcare waste treatment method, and it primarily involves the recycling of placenta.

Currently, there are 13 healthcare waste incinerators operating in Korea, of which three are located in the SCA, and the remaining 10 fall within non-SCA regions [8]. Considering that the half of the total healthcare waste is generated in the SCA, possessing only three of the 13 incinerators pertains to a disproportionately low density. In 2018, the operation rate of these dedicated healthcare waste incinerators rose to 117 %, which is close to the maximum legal operation limit of 130 % [20]; however, despite the urgent need to increase healthcare waste incineration capacity (particularly in the SCA), the expansion or installation of new incinerators is complicated on account of the infectious risks involved.

3.1.3. Korean sterilization and crushing systems

In Korea, healthcare waste treatment is subject to the 'standards and methods for the treatment of wastes' specified in Annex 5 of the Enforcement Decree of the Wastes Control Act [7]. Specifically, healthcare waste should be treated in an incineration or sterilization·crushing facility installed for proper disposal. Infectious and hazardous wastes which are prone to leakage should be treated in a healthcare waste incineration facility, while other healthcare waste should be sent to a sterilization·crushing facility.

Sterilization·crushing facilities in Korea must adhere to the installation standards for waste disposal or recycling facilities outlined in Annex 9 of the Enforcement Decree of the Wastes Control Act [7]. There are three types of sterilization·crushing treatments available: steam, dry heat, and microwave. For steam sterilization·crushing, healthcare waste must be exposed to hot steam of $\geq$121 °C for $\geq$30 min in a sterilization chamber under atmospheric pressure ($\geq$1 bar). Dry heat and microwave sterilization·crushing treatments require a minimum temperature and exposure time of 100 °C for 40 min, and 95 °C for 25 min, respectively [11].

These regulations indicate that the Korean government only permits thermal treatment for healthcare waste in the intermediate treatment phase, and imposes specific environmental conditions, such as temperature, atmospheric pressure, and exposure time for each treatment method. These stringent regulatory restrictions act as a barrier to the introduction of advanced foreign technologies for healthcare waste treatment.

In relation to sterilization testing in sterilization·crushing facilities, Article 41 of the Enforcement Decree of the Wastes Control Act prescribes spore tests as the standard for sterilization·crushing testing [7]. Also, delegates the authority to determine and announce other details to the president of the National Institute of Environmental Research. Detailed test methods are specified in the spore test method of the waste processing testing standard, according to which a minimum reduction of 99.99 % of microbial spores is considered sterile. For microbial spores, standard indicator organisms are designated for each sterilization·crushing facility.

3.2. Test strains for sterilization testing

To identify test strains and sterilization levels for use in sterilization testing, both domestic and foreign data were consulted, and data based on their applicability were selected. For foreign data, guidelines provided by the WHO and STAATT were referred to here; whereas domestic data were obtained from the Agriculture, Forestry, and Livestock Quarantine Headquarters [21–25]. The selection criteria included the ability to culture the strain, and apply it in actual experiments. While the WHO guidelines recommended exposure conditions of at least 121 °C over 30 min, it also noted that effective treatment depends on various factors (time, pressure, treatment procedure), and recommended initial testing based on equipment characteristics along with treatment conditions, in addition to periodic inspection to ensure proper sterilization efficacy. STAATT defines four levels of microbial inactivation for healthcare waste, of which Level III is recommended for appropriate treatment of healthcare waste [26]. Specifically, Level III requires the inactivation of bacteria, fungi, lipophilic·hydrophilic viruses, parasites, and mycobacteria at $\geq 6\ \log_{10}$ reduction, as well as inactivation of *Geobacillus stearothermophilus* and *Bacillus atrophaeus* spores at $\geq 4\ \log_{10}$ reduction. The disinfectant efficacy test guidelines in Korea also specifies standard strains. The strains here were selected after a comprehensive review of domestic and foreign data [11,22,25], in addition to their suitability for use in the planned experiments. All selected test strains are listed in Table 2.

3.3. Sterilization testing in sterilization·crushing facilities

3.3.1. Steam treatment sterilization testing

Sterilization testing conducted under the current legal standard (121 °C·30 min) resulted in a 99.9999 % reduction in spores (*Bacillus atrophaeus*) in both basic and non-crushing treatments. The same results were also achieved in the sterilization testing

Table 2
Strains selected for healthcare waste treatment for this study.

Category	Microorganism for heat treatment	Microorganism for chemical treatment
Spore-forming bacteria	*Bacillus atrophaeus*	*Bacillus subtilis*
Vegetative bacteria	*Staphylococcus aureus*	*Staphylococcus aureus*
Mycobacteria	*Mycobacterium fortuitum*	*Mycobacterium fortuitum*
Fungi	*Candida albicans*	*Aspergilis niger* or *Candida albicans*
Virus	*Bacteriophage*	*Bacteriophage*

conducted on the remaining four strains: *Staphylococcus aureus, Mycobacterium fortuitum, Candida albicans,* and *Bacteriophage*. Likewise, sterilization testing conducted under advanced technological conditions (134 °C·10 min) resulted in 99.9999 % inactivation of spores (*B. atrophaeus*) in both basic and non-crushing treatments, as well as the four remaining strains. In the latter conditions, however, the control groups showed slightly higher inactivation rates for spores (*B. atrophaeus)*, *M. fortuitum* and *C. albicans*, presumably due to the testing being conducted during the summer season, and the storage temperature of the samples not being adequately maintained.

Based on these sterilization testing results, the following conclusions were drawn: First, it is possible to introduce the testing conditions under the advanced foreign technology standard optimized to healthcare waste treatment in steam sterilization·crushing facilities in Korea. The current minimum regulatory temperature and exposure time requirements for steam sterilization·crushing healthcare waste treatment in Korea dictate exposure at 121 °C for 30 min. For this reason, steam sterilization·crushing facility with advanced technology from other countries are not being introduced. Currently, there are domestic companies and hospitals interested in this facility, but installation is being delayed due to regulations. As mentioned before, the facility tested in this study is a high-pressure steam sterilizer that does not crushed because the actual steam sterilization·crushing facility is not allowed in Korea. However, it was set at 134° and 10 min, which are similar conditions to the facility to be introduced. However, the sterilization testing conducted under the advanced technology standard (134 °C·10 min) also resulted in a >99.9999 % reduction in microbial population. These results suggest that the installation of intermediate treatment systems will be expanded in the future if sterilization testing under advanced technology conditions is implemented in sterilization·crushing facilities. Second, various strains may be used for sterilization testing. According to current regulations in Korea, a minimum of 99.99 % reduction in spores (*B. atrophaeus*) must be achieved in order for sterilization testing to be deemed effective. The sterilization tests conducted in the present study resulted in a 99.9999 % reduction in spores, as well as in the remaining four strains tested under both legal standard and advanced technology conditions. In this study, Level III microbial inactivation requirements were met in the sterilization tests for al examined strains. This suggests that intermediate treatment methods can be expanded by permitting the use of a wider range of strains for testing purposes in addition to spores, which are presently the only indicator microorganisms allowed in Korea. If the installation of intermediate treatment methods is expanded in this way, it is possible to treat general healthcare waste, which is the most generated in hospitals. And the sterilized grinding residues can be moved to a general incinerator rather than a medical waste incinerator. This is a stable treatment method that can reduce the burden on the limitations of healthcare waste incinerators. All steam sterilization testing (121 °C·30min·150 kPa, 134 °C·10 min·350 kPa) results in Tables 3 and 4, Fig. 4, Fig. 6.

3.3.2. Microwave sterilization testing

Healthcare waste treatment facilities using microwave technology are currently operated in Korea; thus, the operating conditions for sterilization testing were set to the current legal standard (95 °C·25 min). The sterilization testing on spores (*B. atrophaeus*) achieved a 99.9999 % reduction in the spore population in the basic treatment. The same level of microbial inactivation rates was observed in the sterilization tests on the remaining four strains, namely; however, the control groups showed slightly higher microbial inactivation rates for spores (*B. atrophaeus*) and *M. fortuitum*, likely also due to the high ambient temperature during the summer season and inadequate maintenance of sample storage temperatures.

Based on these sterilization testing results, it was concluded that it is necessary to reconsider the current practice of using only one strain for sterilization tests in Korea's microwave sterilization·crushing facilities. The sterilization tests on the other four strains also resulted in a >99.9999 % reduction in microbial population, suggesting that a wider range of strains could be allowed as indicator microorganisms for microwave sterilization testing in sterilization·crushing facilities, enabling the expansion of intermediate treatment systems in the future. Microwave sterilization testing (95 °C·25 min) results in Table 5, Figs. 5 and 6.

Table 3
Steam sterilization testing (121 °C·30 min·150 kPa) results.

Microorganism	Condition	Pre-treatment count (cfu·g^{-1})	Post-treatment count (cfu·g^{-1})	Sterilization efficacy (%)
Bacillus atrophaeus	Control group	5.8×10^8	1.4×10^8	75.862
	Basic treatment	5.8×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	5.8×10^8	$<1.0 \times 10^1$	99.9999
Staphylococcus aureus	Control group	2.3×10^9	1.4×10^9	39.130
	Basic treatment	2.3×10^9	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	2.3×10^9	2.2×10^2	99.9999
Mycobacterium fortuitum	Control group	6.2×10^8	3.8×10^8	38.709
	Basic treatment	6.2×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	6.2×10^8	$<1.0 \times 10^1$	99.9999
Candida albicans	Control group	1.4×10^8	2.1×10^7	85.000
	Basic treatment	1.4×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	1.4×10^8	$<1.0 \times 10^1$	99.9999
Microorganism	**Condition**	**Pre-treatment count (pfu·g^{-1})**	**Post-treatment count (pfu·g^{-1})**	**Sterilization efficacy (%)**
Bacteriophage	Control group	1.6×10^8	1.6×10^8	0
	Basic treatment	1.6×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	1.6×10^8	$<1.0 \times 10^1$	99.9999

* pfu·g^{-1}: A unit which quantifies the formation of plaque by virus.

Table 4
Steam sterilization testing (134 °C·10 min·350 kPa) results.

Microorganism	Condition	Pre-treatment count (cfu·g^{-1})	Post-treatment count (cfu·g^{-1})	Sterilization efficacy (%)
Bacillus atrophaeus	Control group	5.8×10^8	6.2×10^7	89.310
	Basic treatment	5.8×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	5.8×10^8	$<1.0 \times 10^1$	99.9999
Staphylococcus aureus	Control group	2.3×10^9	1.2×10^9	47.826
	Basic treatment	2.3×10^9	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	2.3×10^9	$<1.0 \times 10^1$	99.9999
Mycobacterium fortuitum	Control group	6.2×10^8	1.7×10^8	72.581
	Basic treatment	6.2×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	6.2×10^8	$<1.0 \times 10^1$	99.9999
Candida albicans	Control group	1.4×10^8	1.1×10^8	21.428
	Basic treatment	1.4×10^8	$<1.0 \times 10^1$	99.9999
	Non-crushing treatment	1.4×10^8	$<1.0 \times 10^1$	99.9999
Microorganism	**Condition**	**Pre-treatment count (pfu·g^{-1})**	**Post-treatment count (pfu·g^{-1})**	**Sterilization efficacy (%)**
Bacteriophage	Control group	1.6×10^8	1.7×10^8	0
	Basic treatment	1.6×10^8	1.0×10^1	99.9999
	Non-crushing treatment	1.6×10^8	1.0×10^1	99.9999

3.3.3. Chemical sterilization testing

During chemical sterilization testing, both peracetic acid and glutaraldehyde treatments achieved a microbial inactivation rate of ≥99.99 % on spores (*B. subtilis*), as well as on the other five strains; however, chemical sterilization testing using sodium hypochlorite produced inconsistent results. While a microbial inactivation rate of 99.9999 % was achieved for *B. subtilis, S. aureus, M. fortuitum, A. niger*, and *Bacteriophage*, only a 99.99 % reduction in the *C. albicans* population was observed, which does not meet the Level III healthcare waste inactivation standard recommended from the WHO.

Based on these results, it was concluded that peracetic acid and glutaraldehyde are effective chemical agents for properly treating healthcare waste if chemical sterilization·crushing methods are allowed in Korea; yet, further research is necessary on the fungal strain *C. albicans* under sodium hypochlorite chemical treatment. For example, the concentration of hypochlorite used in this study was 1000 ppm and the time was 60 min. Additional research is needed to investigate hypochlorite under different conditions. First, the concentration of hypochlorous acid is set to 1,000 ppm or more and the time is fixed to 60 min. Second, the concentration of hypochlorous acid is set to 1,000 ppm and the time is set to 60 min or more. Third, the optimal concentration and time of hypochlorite for *candida albicans* are derived. In this way, it is believed that it will be possible to establish a reference point when using chemical agents as hypochlorous acid in future chemical sterilization·crushing facility. In the future, it is judged that various studies on *candida albicans* are needed under different concentration and time conditions. Chemical sterilization testing results in Table 6, Fig. 7.

4. Conclusions

In Korea, healthcare waste has been steadily increasing. Also, given the current rate of increase, healthcare waste is expected to continue to rise in the future. However, their processing capacity falls short of the total healthcare waste generated, and expanding or constructing new facilities is challenging due to strong opposition from residents and local governments. To address these problems, a stable treatment alternative is being considered, which involves final treatment of healthcare waste in a general incinerator following intermediate sterilization and crushing treatment at large general hospitals.

For sterilization testing, both steam and microwave methods achieved the required microbial inactivation rate of 99.9999 % for all five strains, including spores. Steam treatment also met the microbial inactivation requirement under the advanced technology standard (134 °C·10 min), suggesting the feasibility of introducing various correlated methods, and expanding the range of indicator microorganisms beyond spores in the future. Chemical treatments using peracetic acid and glutaraldehyde similarly achieved a 99.9999 % inactivation rate across all five strains, including spores; however, the chemical treatment using sodium hypochlorite only achieved a 99.99 % reduction in the fungal strain *C. albicans* population, which fails to meet the Level III healthcare waste inactivation standard recommended by the WHO. If chemical treatment methods are allowed in the future, four types of strains, including spores, can be used as indicator microorganisms, while further evaluation is required for *C. albicans*.

The findings of this study are expected to serve as basic data supporting the diversification of sterilization·crushing systems used as intermediate treatment methods for healthcare waste in Korea. In addition, the results of this study provide scientific evidence for increasing their installation. Because there has been no case of sterilization testing for various conditions or strains in order to diversify the intermediate treatment methods of healthcare waste. The practical implications of the research here surround its importance in achieving a reduction of the steadily increasing volume of healthcare waste.

Data statement

Data will be made available on request.

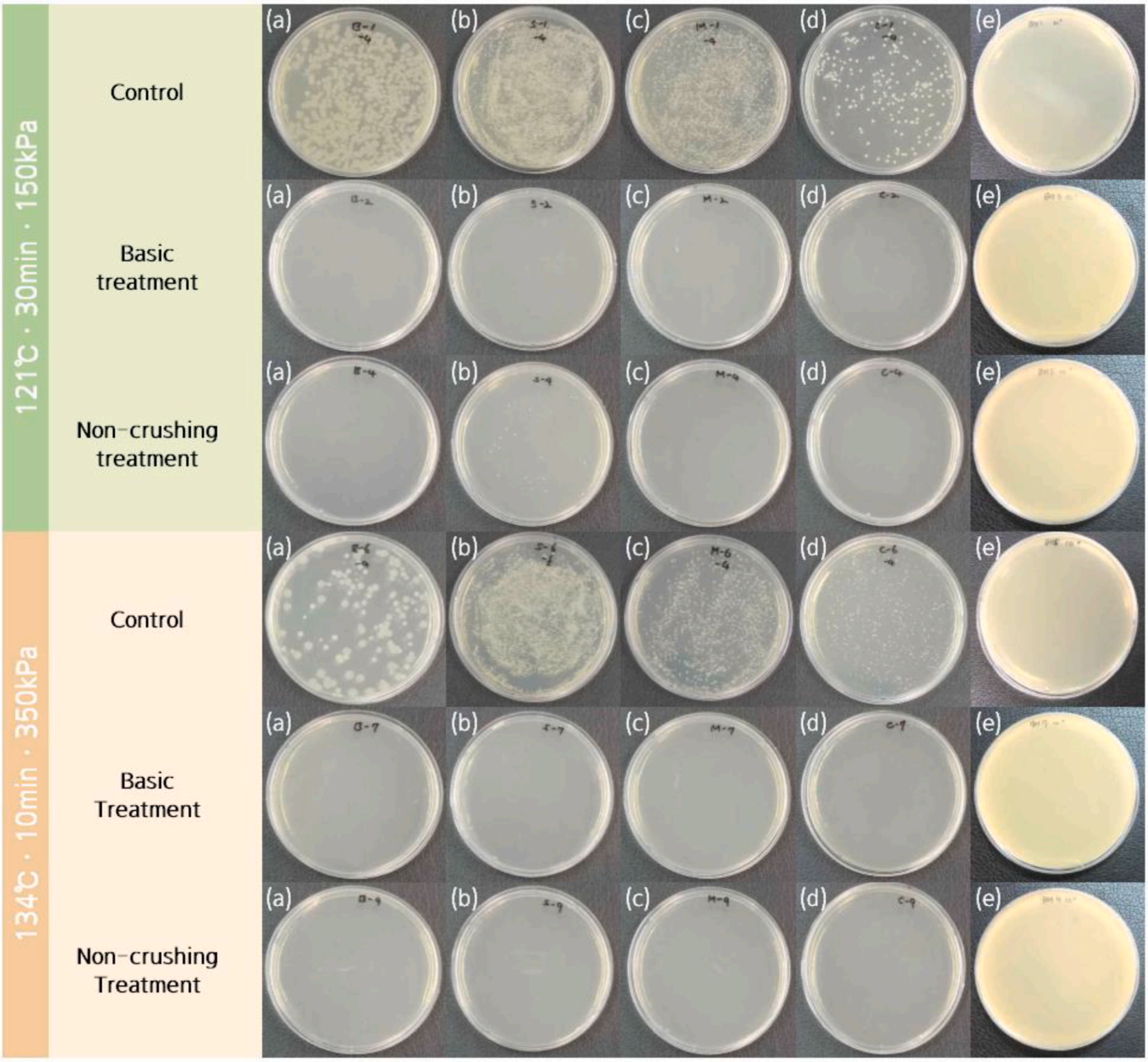

Fig. 4. Sterilization testing results: (a) *Bacillus atrophaeus*, (b) *Staphylococcus aureus*, (c) *Mycobacterium fortuitum*, (d) *Candida albicans*, (e) *Bacteriophage*.

Table 5
Microwave sterilization testing (95 °C·25 min) results.

Microorganism	Condition	Pre-treatment count (cfu·g^{-1})	Post-treatment count (cfu·g^{-1})	Sterilization efficacy (%)
Bacillus atrophaeus	Control group	5.2×10^8	1.0×10^6	99.000
	Basic treatment	5.2×10^8	$<1.0 \times 10^1$	99.9999
Staphylococcus aureus	Control group	3.9×10^8	2.1×10^8	46.153
	Basic treatment	3.9×10^9	$<1.0 \times 10^1$	99.9999
Mycobacterium fortuitum	Control group	2.7×10^8	1.2×10^8	71.428
	Basic treatment	2.7×10^8	$<1.0 \times 10^1$	99.9999
Candida albicans	Control group	2.6×10^7	3.1×10^8	0
	Basic treatment	2.6×10^7	$<1.0 \times 10^1$	99.9999
Microorganism	**Condition**	**Pre-treatment count (pfu·g^{-1})**	**Post-treatment count (pfu·g^{-1})**	**Sterilization efficacy (%)**
Bacteriophage	Control group	2.4×10^8	1.8×10^8	19.915
	Basic treatment	2.4×10^8	$<1.0 \times 10^1$	99.9999

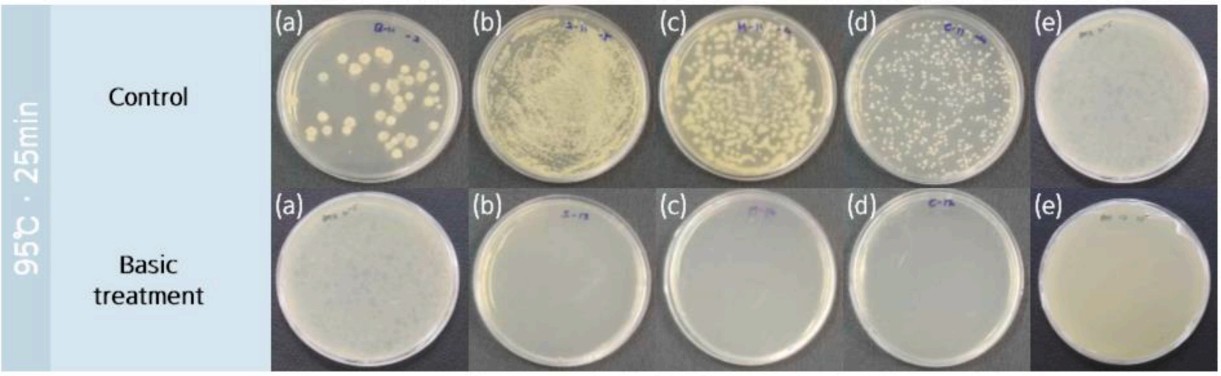

Fig. 5. Microwave testing results: (a) *Bacillus atrophaeus*, (b) *Staphylococcus aureus*, (c) *Mycobacterium fortuitum*, (d) *Candida albicans*, (e) *Bacteriophage*.

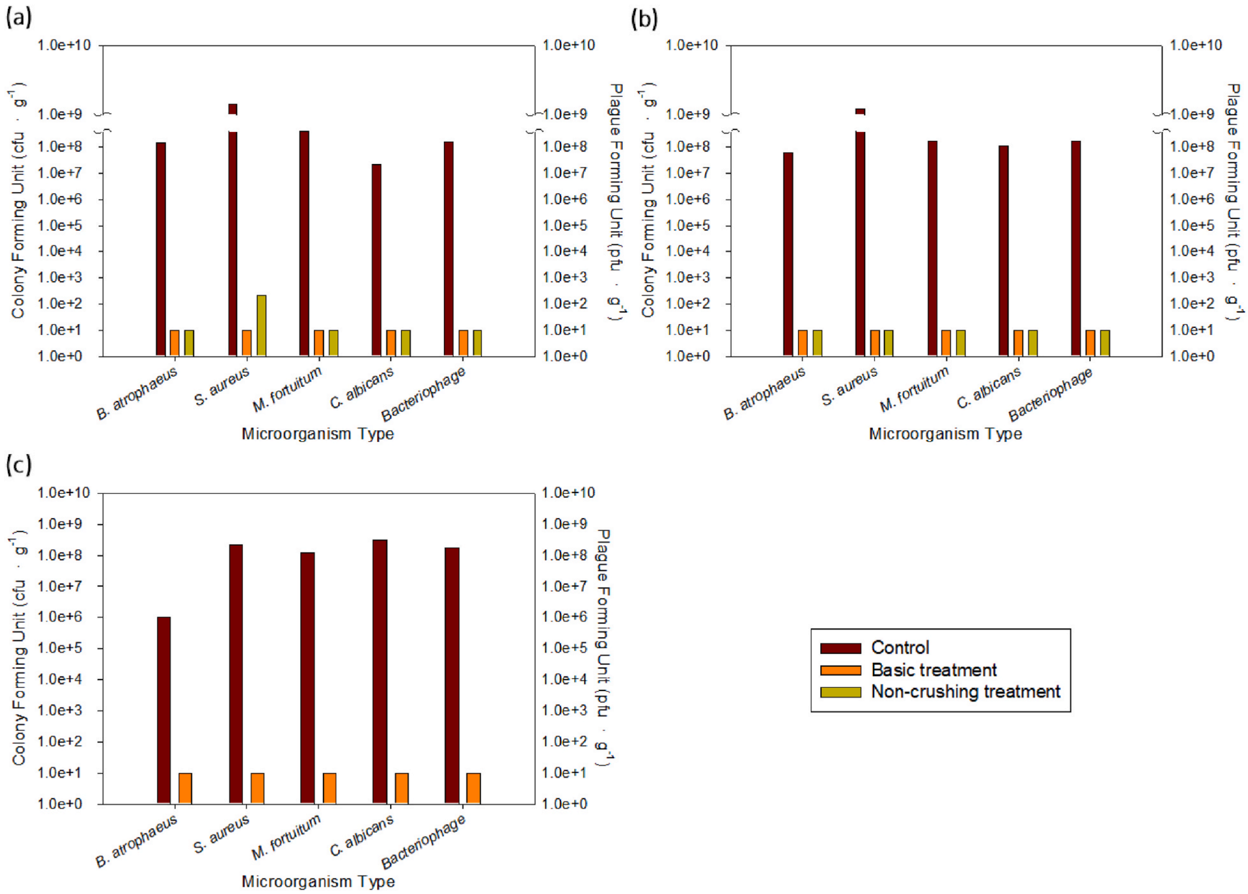

Fig. 6. Sterilization testing results. (a) steam sterilization(121 °C·30min·150 kPa), (b) steam sterilization(134 °C·10 min·350 kPa), (c) microwave sterilization(95 °C·25 min).

Ethics declarations

Review and approval by an ethics committee was not required for this study because this article does not involve any direct experimentation and studies on living beings.

Table 6
Chemical sterilization testing results.

Microorganism	Condition	Pre-treatment count ($cfu·g^{-1}$)	Post-treatment count ($cfu·g^{-1}$)	Sterilization efficacy (%)
Bacillus subtilis	Peracetic acid (2 %)	6.0×10^6	$<1.0 \times 10^1$	99.9999
	Glutaraldehyde (2 %)	6.0×10^6	$<1.0 \times 10^1$	99.9999
	Sodium hypochlorite (1000 ppm)	6.0×10^6	3.0×10^1	99.999
Staphylococcus aureus	Peracetic acid (2 %)	2.3×10^9	$<1.0 \times 10^1$	99.9999
	Glutaraldehyde (2 %)	2.3×10^9	$<1.0 \times 10^1$	99.9999
	Sodium hypochlorite (1000 ppm)	2.3×10^9	$<1.0 \times 10^1$	99.9999
Mycobacterium fortuitum	Peracetic acid (2 %)	6.2×10^8	$<1.0 \times 10^1$	99.9999
	Glutaraldehyde (2 %)	6.2×10^8	$<1.0 \times 10^1$	99.9999
	Sodium hypochlorite (1000 ppm)	6.2×10^8	$<1.0 \times 10^1$	99.9999
Candida albicans	Peracetic acid (2 %)	1.4×10^8	$<1.0 \times 10^1$	99.9999
	Glutaraldehyde (2 %)	1.4×10^8	$<1.0 \times 10^1$	99.9999
	Sodium hypochlorite (1000 ppm)	1.4×10^8	1.0×10^4	99.990
Aspergillus niger	Peracetic acid (2 %)	3.2×10^6	No growth	99.9999
	Glutaraldehyde (2 %)	3.2×10^6	No growth	99.9999
	Sodium hypochlorite (1000 ppm)	3.2×10^6	No growth	99.9999
Microorganism	**Condition**	**Pre-treatment count ($pfu·g^{-1}$)**	**Post-treatment count ($pfu·g^{-1}$)**	**Sterilization efficacy (%)**
Bacteriophage	Peracetic acid (2 %)	1.6×10^8	$<1.0 \times 10^1$	99.9999
	Glutaraldehyde (2 %)	1.6×10^8	$<1.0 \times 10^1$	99.9999
	Sodium hypochlorite (1000 ppm)	1.6×10^8	$<1.0 \times 10^1$	99.9999

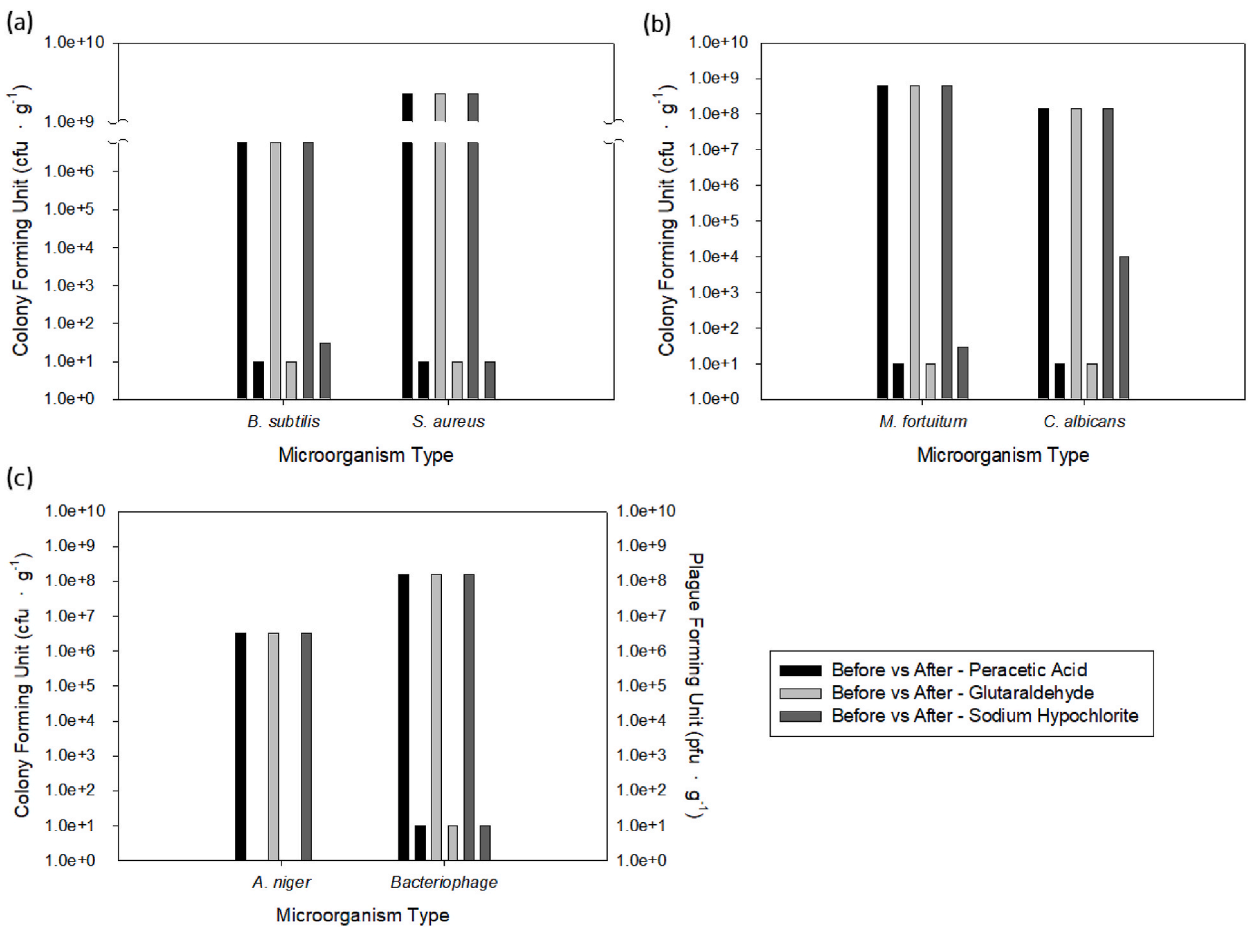

Fig. 7. Sterilization testing results. (a)–(c) chemical sterilization.

CRediT authorship contribution statement

Yoon-Soo Park: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Min-Jung Kim:** Writing – review & editing, Investigation. **Young-Sam Yoon:** Writing – review & editing, Conceptualization. **Tae-Wan Jeon:** Writing – review & editing, Conceptualization. **Hyo-Hyun Choi:** Writing – review & editing, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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