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Technical note

Microwave assisted nanofibrous air filtration for disinfection of bioaerosols

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Abstract

Airborne biological agents, albeit intentionally released or naturally occurring, pose one of the biggest threats to public health and security. In this study, a microwave assisted nanofibrous air filtration system was developed to disinfect air containing airborne pathogens. Aerosolized E. coli vegetative cells and B. subtilis endospores, as benign surrogates of pathogens, were collected on nanofibrous filters and treated by microwave irradiation. Both static on-filter and dynamic in-flight tests were carried out. Results showed that E. coli cells were efficiently disinfected in both static and in-flight tests, whereas B. subtilis endospores were more resistant to this treatment. Microwave power level was found to be the major factor determining the effectiveness of disinfection. Both thermal and non-thermal effects of microwave irradiation contributed to the disinfection. Reducing flow velocity to decrease heat loss yielded higher disinfection efficiency.

1. Introduction

After the anthrax attacks in 2001, concerns regarding infectious bioaerosols in public safety have been brought to light. Bioaerosols vary in size from submicron to a few hundred microns. More specifically, bacteria and fungal spores have sizes ranging from 0.3 to 30 μm, whereas viruses are smaller, ranging from 20 to 300 nm (Hinds, 1999). Through aerosolization, large amounts of biological agents can be dispersed over a wide area in a very short period of time (Ratnesar-Shumate et al., 2008). One can also inexpensively contaminate an entire building by spraying bioaerosol into its ventilation system; for example, a medical nebulizer can be purchased by less than $2. Hence, aerosolization is deemed as one of the most effective methods for biological attacks (Henderson, 1998; Kortepeter & Parker, 1999) and measures to counter such attacks are necessary. The outbreak of Severe Acute Respiratory Syndrome (SARS) in 2003, the long-lasting threat of avian flu and the recent outbreak of the H1N1 Influenza A virus have also raised public awareness of the need to protect the public from natural bioaerosols. In addition, exposure to concentrated airborne microorganisms is associated with allergic diseases (Jo & Seo, 2005; Ren, Jankun, & Leaderer, 1999). All these are calling for better control of exposure to bioaerosols albeit intentionally released or natural (Douwes, Thorne, Pearce, & Heederik, 2003; Lee, Wu, Wysocki, Farrah, & Wander, 2008).
Filtration is one of the most commonly applied methods for air purification. Due to their simple structure and low cost, fibrous air filters are among the most popular ones (Yun et al., 2007). Nanofibrous filtration media have small fiber size, allowing integration of small pore size and large surface areas. Gas slip occurs on nanofibers, which reduces air resistance (Li, Wu, Tepper, Lee, & Lee, 2009; Zhang et al., 2009). All these advantages make nanofiber filtration a promising alternative to existing filters (Barhate & Ramakrishna, 2007). However, air filters alone may not provide sufficient protection against pathogenic bioaerosols, if the captured microorganisms are reentrained into the air. Therefore, it is necessary to add a treatment to the filters to inactivate the microorganisms. Ultraviolet (UV) light is effective in killing bacteria but has limitations on spores (Nicholson, Schuerger, & Setlow, 2005), whereas for a biocidal filter the active chemical is consumed (e.g., by vaporization or reaction) over time (Lee, Wu, Wysocki, Farrah, & Wander, 2008). A remedy to this issue is microwave disinfection. Microwave is an electromagnetic wave with frequencies ranging from 300 MHz to 300 GHz (Jones, Lelyveld, Mavrofidis, Kingman, & Miles, 2002). Volumetric heating, selective heating, and hot-spot effect distinguish microwave heating from conventional heating (Zhang & Hayward, 2006).

Since the mid-1980s, microwave induced/assisted reactions have been studied and widely applied. Among these microwave assisted reactions is the use of microwave irradiation for killing microorganisms (Apostolou et al., 2005; Celanderi et al., 2004; Vaid & Bishop, 1998). Some researchers, especially those among earlier research studies, believe that the microwave inactivates the microbes solely through thermal effects. Goldblith and Wang (1967) studied the effect of microwave irradiation on Escherichia coli (E. coli) and Bacillus subtilis (B. subtilis) and failed to detect any non-thermal effects. Jeng, Kazmerek, Woodworth and Balasky (1987) found no significant non-thermal effects in a dry microwave disinfection process. Fujikawa et al. (1992) investigated the kinetics of E. coli destruction by microwave irradiation and found the difference between microwave exposure and conventional heating was not remarkable. Meanwhile, other studies have reported their observations of non-thermal effect during microwave disinfection of microorganisms. They distinguished the non-thermal effect through examination of damaged cells (Campanha et al., 2007; Celanderi et al., 2004), distorted membrane structure and function (Persson, Salford, Brun, Eberhard, & Malmgren, 1992; Phelan, Neubauer, Timm, Neirenberg, & Lange, 1994), increased release of Ca²⁺, K⁺, DNA, dipicolinic acid and protein (Campanha et al., 2007; Celanderi et al., 2004; Vaid & Bishop, 1998) and altered the enzyme activities (Dreyfuss & Chipley, 1980) after microwave irradiation. Betti et al. (2004) acknowledged the disruption of weak bonds in active protein forms, enhanced production of reactive oxygen species, and cell-signaling pathway interference to microwave non-thermal effects. Watanabe et al. (2000) found that the ionic strength can affect the microwave disinfection rate of microbes and linked the effect to the current within the cells generated by microwave.

All of these past studies about microwave disinfection were conducted in solid, liquid or aqueous phase. None of them was carried out with regard to air filtration. In this study, microwave disinfection was integrated into air filtration process to realize bioaerosol capture and disinfection. The effects of microwave power level and application time were examined. Both vegetative cells and endospores were tested to compare their response to microwave disinfection. Whether non-thermal effect plays a role in disinfection was explored.

2. Materials and methods

2.1. Nanofiber filters

Polyacrylonitrile (PAN) nanofiber filters used in this study were fabricated using an electrospinning process. The details have been presented elsewhere (Zhang et al., 2009) and therefore are not repeated here. During the course of study, it was found that PAN nanofiber thus fabricated did not endure well the heat generated in the microwave oven. So, the filter underwent a 1-h heat treatment at 250 °C to crosslink PAN molecules and produce better heat resistant nanofiber mats. This PAN nanofiber is called crosslinked (or x-linked) PAN in the later text.

Fibers were characterized using scanning electron microscopy (SEM, JSM 6400, JEOL, Japan) and analyzed by ImageJ ver. 1.40 g of National Institutes of Health for fiber diameters. For as-spun PAN fibers, the mean fiber diameter (df) and the coefficient of variation (Cv, the standard deviation divided by the mean value) were 212 nm and 0.206 [number of observations (N)=199], respectively. After the crosslinking process, df and Cv were slightly smaller, 195 nm and 0.166 (N=233), respectively.

The nanofiber mats thus produced were too thin to have the mechanical strength required for practical air filtration. A supporting structure with sufficient mechanical strength was needed. Activated carbon fiber (ACF, American Kynol, Inc., NY) mats are of low cost, easy to obtain, and have a very low pressure drop against the air flow. Hence, in this study, electrospun PAN nanofibers were sandwiched between two ACF mats for testing.

2.2. Preparation of challenging bioaerosols

E. coli, which is often selected as a challenging microorganism for germicidal tests for bioaerosols (Yu, Lee, Lin, & Huang, 2008), was used in this study as a representative of vegetative cells. It is a gram-negative rod-shaped bacterium whose typical size is 0.8 × 2 μm (Sundararaj et al., 2004) with an aerodynamic diameter around 0.8 μm (Li, Hao, Lin, Chang, & Wang, 1999). A non-pathogenic strain (ATCC, no. 15597, VA) was used in this study. It was first inoculated on a Difco...
Nutrient Agar (Becton, Dickinson and Company, lot no.: 8057703, MD) plate from stock. This plate was then incubated at 37 °C for 24 h. Before each experiment, a single colony was picked up, inoculated on a Difco Nutrient Agar slant, and incubated for 24 h. The E. coli population on the slant was then physically removed by a plastic loop and transferred to Ringer’s solution (Fisher, Cat. no.: S77939, NY) and vortexed to prepare the E. coli suspension for bioaerosol generation. Every three days, a new colony was picked up and inoculated into another Difco Nutrient Agar plate to renew the culture.

B. subtilis endospores were tested because of their relative high heat resistivity compared to E. coli. As a gram positive bacterium, B. subtilis has the ability to sporulate and has been used extensively as a benign surrogate to Bacillus anthracis spores (Montville, Dengrove, De Siano, Bonnet, & Schaffner, 2005). B. subtilis endospores are ellipsoidal in shape, approximately 0.8–1.2 μm in length, and have an aerodynamic diameter of 0.9 μm (Aizenberg, Reoone, Grinshpun, & Willeke, 2000). Although considerably resistant to heating, B. subtilis spores have been shown to be inactivated effectively by microwave irradiation in a saline solution (Celandroni et al., 2004). B. subtilis vegetative cells were obtained from the University of Florida Department of Microbiology and Cell Sciences. The vegetative cells were subject to the process outlined by Lee, Wu, Wysocki, Farrah and Wander (2008) to induce sporulation. African violet agar, which included 200 mL African violet soil extract, 800 mL deionized (DI) water, 1 g yeast extract (Fisher Scientific) and 15 g Difco Nutrient Agar was used (ATCC, 1998). B. subtilis vegetative cells were inoculated in this agar and incubated at 36 °C for endospore development. After one week, a 2 mL DI water suspension of B. subtilis was created by vortexing the microbes off the surface of an agar slant. This suspension was heated in a water bath at 80 °C for 30 min to kill the remaining vegetative cells. The suspension was subsequently cooled and centrifuged at 3500 rpm for 10 min to remove cell debris. After applying the malachite green spore-staining technique (Munro, 2000), microscopic analysis showed the absence of vegetative cells in the purified suspension. The spore suspension was used immediately after the purification process.

2.3. Microwave disinfection of bioaerosols

Microwave irradiation was applied to inactivate the microorganisms collected on the filter. The microwave oven used in this study (Panasonic, Model NN-T945SF, 2.45 GHz) operates at the selected power levels and supplies continuous irradiation, i.e. actual adjustment in the intensity of the radiation for the duration of the cook time. To allow aerosols entering and exiting the oven, two 1” holes were drilled into the backside of the oven. The rotating glass plate was also taken out of the oven to reduce energy loss due to its absorbance.

The power levels designated by the manufactures are not equal to the actual amount of energy received by the filter, and it is not trivial to measure the actual microwave energy at any specified point inside the oven. Nevertheless, using the manufacturer’s values does provide insight into the magnitude of microwave irradiation available to the filter and the microbes. Furthermore, it allows comparison with prior studies of microwave disinfection in the literature since that is how it has been reported.

There were two stages of experiments: the first set was a static on-filter disinfection experiment to determine the time scale needed for disinfection. The second set was a dynamic in-flight disinfection, in which microwave irradiation was applied during bioaerosol flight and filtration.

2.3.1. Static on-filter disinfection

The experimental set-up for collecting bioaerosols in the static on-filter testing is shown in Fig. 1. The cylinder air provided clean, dry air with stable flow to the system. The air flow was first split into two ways. The first one led to a 6-jet Collison nebulizer (Model CN25, BGI Inc., MA) with a 5.5 LPM flow rate to generate the testing bioaerosols. The second flow at 11 LPM carried air to the dilution dryer to evaporate water from the aerosol. After passing through the dilution dryer, the aerosol flow was again split into two different paths. The first flow went through the filter holder with a 4.1 LPM flow rate on the filter surface while the excess air was directed to the second air. All rotameters were calibrated against the primary standard before experiments.

The experiments ran for 30 min in order to collect enough microorganisms for adequate experimental resolution. After collection, the filter was taken out of the filter holder and cut into four equal quadrants. Because the ACF mat could ignite in air during microwave irradiation, the PAN nanofiber layer was peeled off the ACF mat. One of the quadrants was directly inoculated into 50 mL of Ringer’s solution and vortexed to extract the microorganisms. This inoculated solution was serially diluted, plated and incubated at 37 °C for 24 h. The number of colony forming unit (CFU) on the plates was then counted. Only plates with between 30 and 300 units were counted. The remaining quadrants were placed between two SiC disks (Vesuvius, 47 mm OD × 20 mm thickness, 45 PPI, OBSIC, lot no.: AL7370101L) and heated in the microwave oven for varying periods of time (30, 45, 60 and 90 s) to determine the microwave disinfection efficiency and to ascertain how long it would take to completely sterilize the bioaerosols by microwave irradiation. SiC disks were used because they are a good microwave absorber and can be quickly heated by microwaves. After microwave irradiation, the quadrants were also inoculated into the Ringer’s solution and cultured as described above. In the case that had no plate with more than 30 colonies, the plate of the lowest dilution level was analyzed. The survival fraction (S) on the filter was then calculated as $S = c_t / c_0$, where $c_t$ is the viable bioaerosol concentration of the quadrant treated in microwave for time $t$, and $c_0$ is the viable bioaerosol concentration of the quadrant without microwave treatment. Additionally, to verify that the 4 quadrants collected similar amounts of microorganisms, a triplicate set of control tests (where all of the 4 quadrants were not
microwaved) were carried out for *E. coli*. Results showed that the average coefficient of variation (CV) was 32%. Hence, the deviations are insignificant considering that microwave disinfection is measured logarithmically.

### 2.3.2. Dynamic in-flight disinfection

In this stage, microwave disinfection was integrated into the filtration process. This is a new approach that had not yet been investigated by others. Because common filter holders may be damaged under direct microwave exposure, a pure quartz filter holder that is transparent to microwave was designed and placed inside the microwave oven. This holder can hold a standard 47 mm diameter round filter; however, the effective diameter of the filter is only 40 mm due to the filter holder structure. Noncombustible SiC mats (plain weave ceramic grade Nicalon cloth, COI Ceramics, UT) were used in this unit to provide adequate mechanical support for the PAN nanofiber filter media. In initial spore experiments, SiC mats were also used but were later replaced by SiC disks for their superior heating properties.

The experimental set-up for the in-flight tests is also shown in Fig. 1. The air flow rates supplied to the nebulizer and the dilution dryer were both set at 6 LPM to produce a suitable relative humidity (about 50%) for the biological testing (Cox & Wathes, 1995; Wang & Brion, 2007). After the dilution dryer, the air flow was split equally into three paths of 4 LPM each. The first path was directed to the quartz filter holder inside the microwave oven. The pressure drop across the filter was monitored by a differential pressure gauge and the flow rate across the microwave/filtration system was adjusted according to the pressure drop. The corresponding face velocity across the filter holder was 5.3 cm/s based on the effective filter diameter in the holder (40 mm). The second 4 LPM split stream was directed to a filter holder outside the microwave oven with an identical filter type as was present in the microwave oven. The third split stream was directed to a Biosampler (SKC, Eighty-Four, PA) without any filter to determine the feed concentration. A vacuum pump (Model no.: RVE56B17FS305A, Marathon Electric, WI) was used to draw air from the system in order to prevent pressure build up in glass joints, which would otherwise be forced apart. Low numbers of CFU were noticed in the preliminary *B. subtilis* spore data due to the endospore purification process, in which some vegetative cells in the culture did not fully sporulate and were killed when subjected to heat. Therefore, the flow rates of the system were increased by 25% for the spore tests.

The filter inside the microwave oven was labeled F1 and the filter outside was labeled F2. The on-filter survival fraction under microwave irradiation could be calculated by comparing the viable counts on the two filters (F1/F2). The bioaerosol collection and disinfection was carried out for 30 min of three 10-min-cycles for each experiment. Different microwave power levels and microwave application times were combined and used as microwave irradiation conditions. Testing without filters or microwave irradiation was also conducted to ensure there was an even distribution of bioaerosols across the system. During this testing, Biosamplers were attached to both control and experimental paths and then microbes were aerosolized from the nebulizer. Both *species* were tested, with triplicates each time. The samples cultured from the Biosamplers demonstrated less than 5% difference in CFU between control and experimental lines. This indicates that any wall loss was independent of the path taken.

![Fig. 1. Experimental set-up for static loading tests and dynamic in-flight disinfection tests.](image-url)
3. Results

3.1. Static on-filter disinfection

Six sets of the static on-filter E. coli disinfection tests were carried out at 500 W microwave power. As shown in Table 1, in less than 90 s the survival dropped below the detection limit. These results suggest that microwave irradiation can effectively disinfect E. coli collected on the filtration media. With a working frequency of 2.45 GHz, the microwave has a wavelength of 12.2 cm. The large standard deviation shows that the position in the microwave oven may be critical to the disinfection rate.

B. subtilis spore tests show a similar trend in log-disinfection. As shown, after irradiation at 750 W for 90 s, 2.7 logs disinfection of the spores was observed. Less powerful microwave power applications proved less effective. For 250 W, 45 s of application time was required to achieve any disinfection at all. Compared with E. coli tests, B. subtilis spores were more difficult to destroy, requiring irradiation at 750 W for 90 s for ~3 logs disinfection. This apparent difficulty in destroying the spores would also be observed during in-flight testing.

3.2. Dynamic in-flight disinfection

In this stage, all combinations of the three power levels (500, 250, and 125 W) and four application times (continuously, last 5, 2.5, and 1.25 min of each 10-min-cycle) were tested in triplicate. The dynamic in-flight disinfection (the F1/F2 value) of E. coli as a function of microwave application time at three microwave power levels is displayed in Fig. 2. When 500 W microwave power was used, at least 3.7 logs of the viable E. coli were disinfected regardless of whether the microwave was applied to the system continuously (10 min per 10-min-cycle), or periodically (5 or 2.5 min per 10-min-cycle). This suggests that 2.5 min per cycle is sufficient to disinfect the E. coli. At a lower power level, less disinfection was achieved.

Table 1
Survival fraction of microorganisms under microwave irradiation—Static on-filter disinfection.

|                          | Microwave irradiation time | 
|--------------------------|----------------------------|
|                          | 30 s | 45 s | 60 s | 90 s |
| **E. coli (500 W)**      |      |      |      |      |
| Mean (%)                 | 2.38 | –    | 0.46 | < 0.17 |
| SD (%)                   | 3.20 | –    | 0.64 | 0.22 |
| **B. subtilis spores (250 W)** |     |      |      |      |
| Mean (%)                 | 100  | 93.3 | 30.2 | 2.19 |
| SD (%)                   | 0.013| 1.04 | 1.43 | 0.75 |
| **B. subtilis spores (750 W)** |    |      |      |      |
| Mean (%)                 | 74.0 | 6.00 | 1.26 | 0.20 |
| SD (%)                   | 7.42 | 2.04 | 0.87 | 0.15 |

![Fig. 2](image) Dynamic in-flight on-filter disinfection of E. coli as a function of microwave application time at three microwave power levels using SiC mats.
A two-way ANOVA test using Minitab 15 statistical package identified that the microwave power was the major factor that affects the *E. coli* disinfection (*p*-value=0.003). On the other hand, the microwave application time did not exhibit a significant influence (*p*-value > 0.3).

Experiments were then carried out without the use of filters. Under continuous 500 W microwave power, about 1.3 logs of *E. coli* were lost during flight across the microwave field (i.e. filter holder in the microwave oven). The corresponding exposure time to microwave was less than 5 s, which most likely resulted in a limited heating effect. This is suggested by the calculations of Canals et al. (1999) where a micrometer sized aerosol was found to experience a temperature increase of only 1 K for a 5 s residence time in a relatively strong microwave field. The results suggest direct microwave non-thermal effect can disinfect biological agents to certain extent, at least for vegetative cells like *E. coli*.

An identical set of experiments, using the SiC mats, were conducted in triplicate for the *B. subtilis* spore aerosols. Crosslinked PAN filters were used because of their resistance to heat allowing high temperature spore testing. At the highest power of 500 W and continuous 30-min application time, microwave disinfection was only 1 log (results not shown). Unlike the *E. coli* tests where nearly complete microorganism disinfection was observed, a large percentage of viable *B. subtilis* spores remained on the experimental filter. At the lowest setting of 125 W and 1.25 min/10-min-cycle periodic application time, no disinfection was observed.

Because of inadequate spore disinfection, the SiC mats were replaced by SiC disks, and the maximum application power was increased from 500 to 750 W. Results with these changes, displayed in Fig. 3, showed considerable increase in spore disinfection. With continuous microwaving at 750 W, about 2.8 logs disinfection was observed. Comparing to the *E. coli* results, spore disinfection is still less effective. This result is likely attributed to the heat resistivity of the endospores. Although complete disinfection could potentially be achieved by increasing the microwave power further, the durability of the filter in such conditions was a concern. Irradiation at 750 W for extended periods of time was found to degrade the mechanical efficiency of even the crosslinked PAN filter. After irradiation for continuous 30 min, slight discoloration and burning of the filter was noticed.

It was noticed that the static experiments had greater inactivation than the in-flight experiments under similar conditions. Because of this, it was hypothesized that heat loss to the flow from the filter caused decreased inactivation during the in-flight experiments. Hence, experiments were conducted to decrease face velocity during irradiation (at the same microwave power level) to verify the hypothesis. For the 750 W and 1.25 min condition, decreasing the face velocity 50% during irradiation resulted in an increase of 0.636 log removal of spores. This result provides evidence that heat conduction to the flow affects microbial inactivation on the filter. It also provides evidence that thermal effects, rather than non-thermal effects, may be the dominant factor in spore inactivation.

ANOVA statistical analysis indicated that microwave power, rather than application time, was the most significant factor in the reduction of viable *B. subtilis* spores on the filter (*p*-value < 0.05). Therefore, to maximize the effects of microorganism disinfection on PAN nanofiber filters, microwave power should be the most important consideration for
in-flight disinfection. In optimizing this disinfection process, the highest microwave power should be selected (without possible damage to the filter) with a short application time.

4. Discussion

Several other research studies also reported the E. coli disinfection rate under microwave irradiation. Table 2 is a detailed summary of these results. As shown, 5–7 logs of viable E. coli are usually inactivated within 30–60 s when microwave power is higher than 800 W. However, in the present study, because of the high retention of the nanofiber filters, it was not possible to extract enough viable particles from the filter in order to yield a control plate with more than 10^5 CFU of E. coli. Hence, disinfection of more than 5 logs was not achievable in the present study. Table 2 also shows that E. coli disinfection can be significantly accelerated if some assisting approach is added to the microwave irradiation, such as argon plasma and catalytic reactions. It should be noted that only the present study was conducted in air whereas all previous studies were conducted in an aqueous system or a medium containing significant amount of water.

The spore experiments reflect the first attempts to inactivate B. subtilis endospore aerosols with microwave irradiation. Celandroni et al. (2004) observed complete disinfection of B. subtilis spores in a 0.25 mL saline solution under 100 W microwave for 20 min where boiling occurred within 45 ± 5 s. Because a different heating medium and setup was used, it is not appropriate to compare their results directly to the present study. In the previous study, spores were suspended in a solution during irradiation while in this study spore aerosols were collected on microwave transparent PAN fibers which required SiC disks for heating. Although fiber heating occurred by conduction with the SiC disks rather than direct heating by radiation, the SiC disks were able to reach a much higher temperature than boiling water near 100 °C. Therefore, the method developed in this study has greater potential for faster spore disinfection.

The results of this study demonstrate the effectiveness of microwave radiation to disinfect air filters. Compared to other filter disinfection methods, the use of microwaves proved superior with respect to the magnitude of inactivation and the application time required. For example, a study investigating UV irradiation of air filter media required 1 h to achieve 97% inactivation of collected Mycobacterium parafortuitum. For the fungal spore Aspergillus versicolor, only 75% on-filter inactivation was achieved under the same conditions (Kujundzic et al., 2006). Similarly, another study involving microorganism inactivation by photocatalysis of a TiO2 filter by UV required hours for 50% inactivation of bacteria (Lin & Li, 2003). Compared to these two studies, the results of the present study indicate that microwaves have significant potential in air filter disinfection.

While encouraging spore disinfection on the filter was achieved (2.8 logs), B. subtilis spores were significantly more challenging to inactivate than E. coli, and it requires much higher microwave settings for similar results. It is of great interest to monitor the real-time temperature pattern on the filter surface during irradiation and the disinfection temperature of the microorganism for better understanding of the whole process that will be helpful in improving the effectiveness of the system. However, due to technical limitations, real-time measurement was not conducted in this study. There are several ways that may be possible for the monitoring, including fiber optical temperature measurement, pyrometer, infrared (IR) cameras, etc., that can be considered in future works.

Table 2
E. coli disinfection by microwave irradiation in the present study in comparison to those reported in literature.

| Research               | Disinfection rate | Microwave application time (s) | Microwave power a (W) | Assisting approaches | E. coli surviving media |
|------------------------|-------------------|--------------------------------|------------------------|----------------------|-------------------------|
| Goldblith and Wang (1967) | 6 logs            | 50                             | N/A b                  | None                 | PBS c                   |
| Fujikawa et al. (1992)   | 6 logs            | 90                             | 300                    | None                 | PBS                     |
|                        | 4 logs            | 150                            | 200                    | None                 | PBS                     |
|                        | 5 logs            | 240                            | 100                    | None                 | PBS                     |
| Watanabe et al. (2000)   | 3 logs            | 50                             | 500                    | None                 | PBS                     |
| Apostolou et al. (2005)  | 6 logs            | 35                             | 800                    | None                 | Small chicken portion   |
| Awuah et al. (2005)      | 7 logs            | 35                             | 1200                   | None                 | Milk                    |
| Park et al. (2006)       | 5 logs            | 30                             | 1000                   | None                 | Sponge                  |
|                        | 6 logs            | 60                             | 1000                   | None                 | Scrubbing pads          |
| Park et al. (2007)       | 4 logs            | 1                              | 1000                   | Argon plasma         | Saline e                |
| Takashima et al. (2007)  | 8 logs            | 5                              | 100                    | Catalytic reaction   | NB e                    |
| Present study            | > 4 logs          | 90                             | 500                    | None                 | Nanofiber filter        |

a Microwave energy at the application target may not equal microwave operating power.

b Not mentioned by the authors.
c Phosphate buffer solution.
d Normal saline, 0.9% NaCl water solution.
e Nutrient broth, Eiken Chemical Co. Ltd., Tokyo, Japan.
5. Conclusions

Microwave assisted nanofibrous filtration is demonstrated to be an effective and efficient approach for disinfecting airborne pathogens. Microwave power is found to be the major factor affecting the effectiveness of disinfecting biological agents, whereas microwave application time is a less significant factor in the process. Endospores such as *B. subtilis* spores do need a higher microwave power to be efficiently disinfected than vegetative cells such as *E. coli* due to their resistivity to heat. On the other hand, microwave non-thermal effect was observed by an experiment running without a filter. Reducing flow velocity to decrease heat dissipation would also enhance disinfection efficiency. In order to further understand and optimize this process, future works are needed to measure real-time temperature on the filter surface and to provide a more uniform electric field in the microwave oven.

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