



Decontamination Assessment of Nanofiber-based N95 Masks

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Abstract

As the world battles with the outbreak of the novel coronavirus, it also prepares for future global pandemics that threaten our health, economy, and survivor. During the outbreak, it became evident that use of personal protective equipment (PPE), specially face masks, can significantly slow the otherwise uncontrolled spread of the virus. Nevertheless, the outbreak and its new variants have caused shortage of PPE in many regions of the world. In addition, waste management of the enormous economical and environmental footprint of single use PPE has proven to be a challenge. Therefore, this study advances the theme of decontaminating used masks. More specifically, the effect of various decontamination techniques on the integrity and functionality of nanofiber-based N95 masks (i.e. capable of at least filtering 95% of 0.3 μm aerosols) were examined. These techniques include 70% ethanol, bleaching, boiling, steaming, ironing as well as placement in autoclave, oven, and exposure to microwave (MW) and ultraviolet (UV) light. Herein, filtration efficiency (by Particle Filtration Efficiency equipment), general morphology, and microstructure of nanofibers (by Field Emission Scanning Electron microscopy) prior and after every decontamination technique were observed. The results suggest that decontamination of masks with 70% ethanol can lead to significant unfavorable changes in the microstructure and filtration efficiency (down to 57.33%) of the masks. In other techniques such as bleaching, boiling, steaming, ironing and placement in the oven, filtration efficiency dropped to only about 80% and in addition, some morphological changes in the nanofiber microstructure were seen. Expectedly, there was no significant reduction in filtration efficiency nor microstructural changes in the case of placement in autoclave and exposure to the UV light. It was concluded that, the latter methods are preferable to decontaminate nanofiber-based N95 masks.

Keywords Face masks, nanofibers · Filtration efficiency · Pressure drop · Microstructure

Introduction

Face masks are among the most important personal protective equipment (PPE) that are proven to reduce transmission risks of infectious airborne particles (Paxton et al. 2020). Airborne particles containing hazardous pathogens such as harmful viruses can cause serious health concerns from mild symptoms to, in the case of SARS, MERS, or the recent SARS-Cov-2, acute illness and even death (Bałazy et al. 2006). In a recent study by

Huang et al., ‘increased availability of PPE’ ranks among the top four effective government intervention tactics to combat COVID-19 (Haug et al. 2020). Masks are particularly important because they can both be used to protect the user from infectious airborne viruses as well as to prevent further spread of the virus from the infected user. However, in the midst of a pandemic, surging demand for masks has increased concerns about their adequate supply (Mackenzie 2020; Liao et al. 2020). To respond to the current global needs, various studies have examined a number of decontamination techniques for the purpose of reusing masks (Fischer et al. 2020; Grinshpun, Yermakov, and Khodoun 2020; O’Hearn et al. 2020; Probst et al. 2020; Rubio-Romero et al. 2020; Viscusi, King, and Shaffer 2007; Smith et al. 2020; Fischer et al. 2020; Lore et al. 2012; Viscusi et al. 2009; Bergman et al. 2010; Viscusi et al. 2011; Gertsman et al. 2020; Woo et al. 2012; Bopp et al. 2020; Lowe et al. 2020; Juang and Tsai 2020; Yang et al. 2020). While masks fabricated by the conventional

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melt-blown technique (Sureka, Garg, and Misra 2020) are the subject of these studies, with the advent of nanofiber technology and their use in production of masks (Teby-eteckerwa et al. 2020) and given the structural differences between the two, in this study changes in filtration efficiency, pressure drop, and microstructure of nanofiber-based masks post decontamination by chemical, irradiation, wet and dry heat are examined and discussed.

Although many potentially hazardous airborne viruses are in the range of hundreds of nanometers (Leung and Sun 2020), for the most part they can only travel when they are suspended in relatively large liquid droplets (Fennelly 2020). That is why standard N95 masks are considered adequate to capture most airborne particles (Paxton et al. 2020; Leung and Sun 2020). According to the National Institute for Occupational Safety and Health (NIOSH) regulations, 42 CFR 84 (NIOSH 1997), N95 masks must be able to prevent traverses of at least 95% of 0.3 μm sodium chloride (NaCl) aerosol Particulate Matters (PM) (Bałazy et al. 2006). In addition, the pressure drop across the filtration layer at 85 $\text{L}\cdot\text{min}^{-1}$ must be blow 350 Pa (Konda et al. 2020). While conventional N95 masks based on melt-blown fabrication technique are arguably ineffective for particle size range of 0.1–0.3 μm (Bałazy et al. 2006), researchers have turned to nanofibers for their higher surface area and smaller pore dimensions which provide enhanced filtration efficiency (Bałazy et al. 2006; Zhang et al. 2016; Wang et al. 2017). As seen in figure 1, a nanofiber-based mask is consisted of up to five nonwoven layers of which the middle layer is coated with nanofibers. In this configuration, highly porous and uniform structure of nanofibers allow air molecules to easily pass through the layers and as the result, this type of filtration is associated with a considerable lower pressure drop and improved breathability (Zhu et al. 2017).

Material and methods

Treatment methods and related conditions employed in this study are tabulated below (see Table 1). This selection was inspired by several other studies that examined the integrity of melt-blown based N95 masks after decontamination. In this study, all disposable nanofiber-based N95 masks were provided by [®]Rima (FNM, Iran). For every method, three masks were randomly selected and grouped. All masks in this investigation came from a same production batch.

Treatment methods

Chemical (n=6):

The randomly selected masks were soaked in 70% ethanol (Pars, Iran) overnight to dry by air at room temperature (RT). In the case of bleaching, other samples were submersed in a bleaching solution of 0.5% sodium hypochlorite (Whitex Chemical Company, Iran) for 10 min, then rinsed with water and left to dry by air at RT for more evaluation.

Wet heat (n=9):

Boiling water, steaming on boiling water and autoclave (Reyhan Teb, RT2, 75) were applied to masks in this treatment group. Three samples were immersed in boiling water for 5 min. Another three samples were fixed on the top of a boiling water beaker to undergo steam for 10 min (applied to both sides). The last three samples in this group were autoclaved in individually laminated bags and treated at 121°C for 20 min.

Dry heat (n=6):

A static-air oven (Shimaz Co, Iran) was used for treating of three masks at 75°C for 30 min. Another three samples

Fig. 1 Structural layers of a nanofiber-based mask

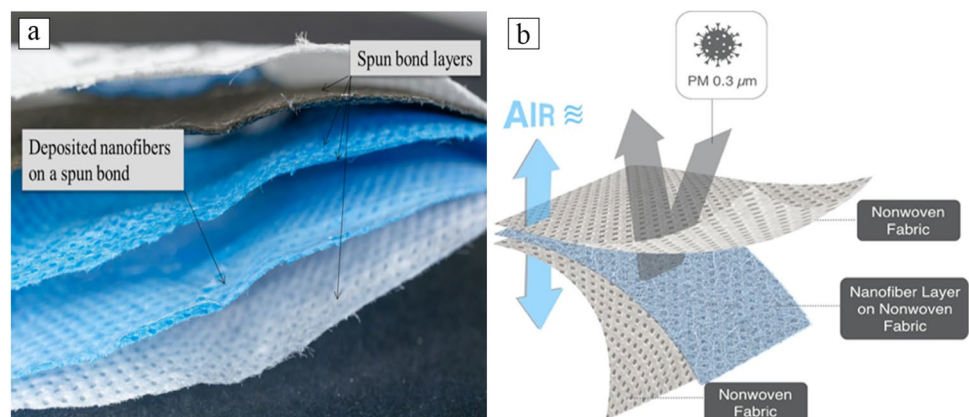


Table 1 Decontamination methods of nanofiber-based N95 masks

| Treatment | Mode of Application | Temperature (°C) | Time (min) | Ref. |
|---|---|---------------------|------------------|-----------------------------------|
| Chemical | | | | |
| Ethanol | Soaking in ethanol (70%) bath | RT* | 1 min | (Smith et al. 2020) |
| Bleach | Soaking in diluted sodium hypochlorite (0.5%) | RT | 10-30 min | (Viscusi, King, and Shaffer 2007) |
| Wet heat | | | | |
| Autoclave | Autoclaved in individually laminated bags | 121 | 30 in | (Bopp et al. 2020) |
| Steam | Steaming on boiling water | 100 | 10 min each side | (Liao et al. 2020) |
| Boiling | Soaking in boiling water | 100 | 5 min | (Juang and Tsai 2020) |
| Dry heat | | | | |
| Oven | Static-air oven | 75 | 30 min | (Liao et al. 2020) |
| Ironing | Dry ironing | 150 | 5 secs | (Lakdawala et al. 2011) |
| Irradiation | | | | |
| Ultraviolet Germicidal Irradiation (UVGI) | Irradiated in UVGI cabinet (~250 nm, 6 W) | RT | 30 min each side | (Lowe et al. 2020) |
| Microwave | Irradiated in Microwave oven, 2450 MHz | Cabinet temperature | 10 min | (Zhang et al. 2010) |

*RT: Room Temperature

underwent ironing by a Philips ultra-smooth glide domestic iron set for about 5 seconds (150-170 °C). To avoid melting of the outer spun bond layer, the masks were covered with a cotton fabric.

Irradiation (n=6):

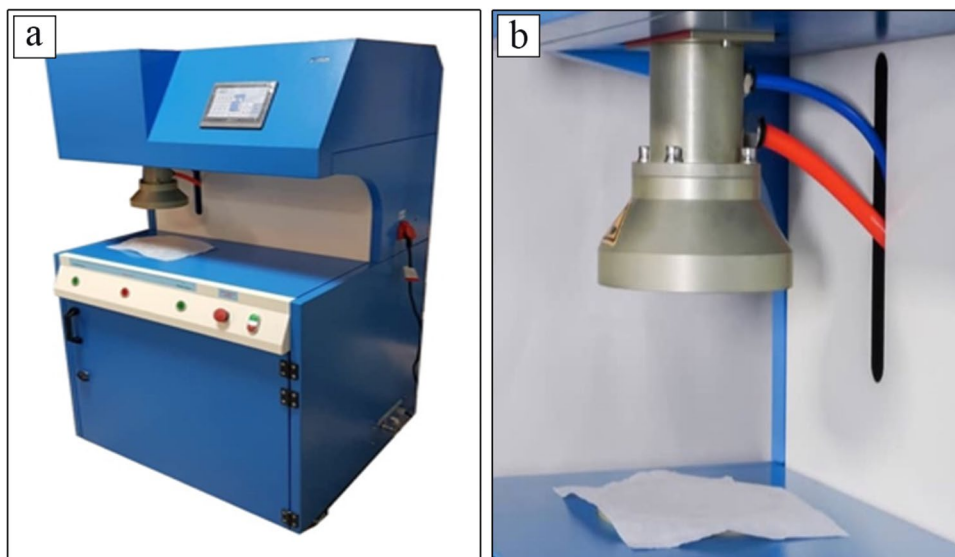
Three samples were placed separately inside a microwave (Techno Microwave Co, Iran) for 10 min to receive radiation. In order to avoid burning or melting, samples were first soaked in water prior to any microwave application. Also, in this group another three samples received Ultraviolet

Germicidal Irradiation (UVGI) radiation using [®]OsrumUVC lamp (~250 nm, 6W) for 20 min on each side.

Filtration efficiency and pressure drop

Treated samples plus three untreated samples that serve as control (n=30) were individually mounted on a custom-made opening (see figure 2) of a Particle Filtration Efficiency (PFE) equipment (FT150EA, FNM, Iran) that is equipped with a differential pressure transmitter (Rosemount Company, US). To evaluate filtration efficiency and pressure drop before and after treatment the PFE equipment is

Fig. 2 Particle Filtration Efficiency equipment to evaluate filtration efficiency



equipped with an opening area of 100 cm² at 85 lpm. The measurement of the pressure drop in this equipment is based on a method described in a standard NIOSH documentation where the flow rate is calibrated to 85 lpm with a tolerance of ± 1.4 lpm.

Field Emission Scanning Electron Microscopy (FESEM)

The morphology of nanofiber structure in every sample ($n=30$) was characterized using a Field Emission Scanning Electron Microscope (FEI NOVA NANOSEM 450, USA) at an accelerating voltage of 10 kV. Briefly, the samples were mounted onto aluminum stubs covered with conductive carbon tape. Then samples were gold-sputtered and the FESEM images were recorded.

Statistical methods

All experiments were done in triplicate. SPSS 18.0 statistical software (SPSS Inc., Chicago, IL, USA) was used to perform statistical analysis. Differences were determined by one-way ANOVA, followed by post-hoc Scheffe's test method comparison. The obtained data are expressed as mean \pm standard deviation. Significant difference between groups was awarded when $p < 0.05$.

Results and Discussion

As the pandemic due to COVID-19 takes its course around the globe, demand for protective gears such as face masks markedly increases. Evidently, in order to prevent virus transmission, health officials instruct citizens to wear masks when in public (Organization 2020; Cheng et al. 2020). This has led to a significant surge in demand for efficient masks in many places around the world. In addition, the cost of using

a mask per person per day can lead to a mounting financial burden, especially for low-income families and those living in the developing world. Consequently, various decontamination protocols for the purpose of reusing masks have been proposed (Fischer et al. 2020; Grinshpun, Yermakov, and Khodoun 2020; O'Hearn et al. 2020; Probst et al. 2020; Rubio-Romero et al. 2020; Viscusi, King, and Shaffer 2007; Smith et al. 2020; Fischer et al. 2020; Lore et al. 2012; Viscusi et al. 2009; Bergman et al. 2010; Viscusi et al. 2011; Gertsman et al. 2020; Woo et al. 2012; Bopp et al. 2020; Lowe et al. 2020; Juang and Tsai 2020; Yang et al. 2020). Nevertheless, concerns on filtration efficiency and mask integrity post decontamination treatment are still apparent.

While conventional masks fabricated by melt-blown technology (Sureka, Garg, and Misra 2020; Tsai 2020) have been the target of several decontamination studies (Fischer et al. 2020; Yang et al. 2020; Woo et al. 2012), in this manuscript, nanofiber-based masks are subject to chemical (ethanol, and bleaching), wet heat (boiling, steam, and autoclave), dry heat (oven, ironing), and irradiation (microwave and UVGI) treatment protocols and analyzed. More specifically, filtration efficiency and morphology of nanofibers before and post-treatment have been assessed.

In order to examine structural integrity of the samples, SEM and FESEM images of polyamide 6 (PA6) electrospun nanofibers were obtained. Figure 3.a shows a cross-sectional SEM image of the nanofibers on a nonwoven substrate. These structures are in fact what will be found inside nanofiber-based N95 masks. The average diameter of the nanofibers is 163 ± 43 nm (see Figure 3b and 3c). The illustrated nanofiber layer with submicron pore size enables efficient filtration of particles larger than $0.3 \mu\text{m}$ (PM $0.3 \mu\text{m}$). The ultrafine nanometer with the thickness of about 20 nm, formed within the nanofibrous structures that helps trap up to 95% of PM $0.3 \mu\text{m}$ with a pressure drop range of 110–330 Pa (at $85 \text{ L}\cdot\text{min}^{-1}$), which follows the standard NIOSH guidelines for N95 masks (Zhang et al. 2016).

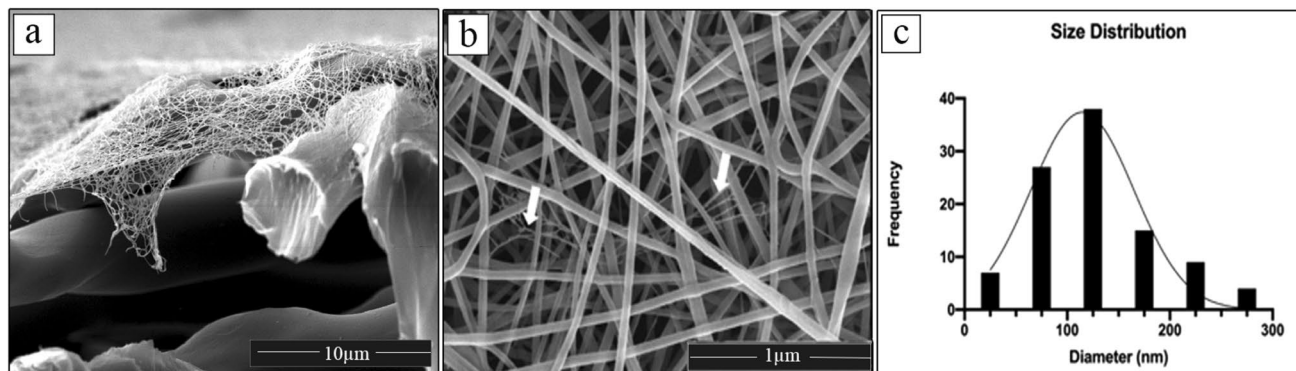


Fig. 3 a) Cross-sectional SEM image of PA6 electrospun nanofibers deposited on a nonwoven fabric, b) FESEM image of PA6 electrospun nanofiber layer, arrows show formation of nanonets between nanofibers, c) Diagram shows the size distribution of PA6 electrospun nanofibers

Other than structural integrity, performance integrity of the samples is also of vital importance. These are measurements of i) pressure drops across the fabric, otherwise known as breathability of the fabric, and ii) filtration efficiency of the samples to capture specific size range of aerosols. In fact, these deciding parameters place a sample in the N95 category according to the NIOSH system. In order to compare the performance integrity of the samples before and after decontamination, all samples underwent PEE treatment. Table 2 tabulates the results of this investigation.

Ethanol

Expectedly, soaking samples in 70% ethanol has been shown effective for inactivation of viruses and bacteria situated on N95 masks (Fischer et al. 2020; Lin et al. 2018). However, in contrast to the virucidal and bactericidal effectiveness, filtration efficiency of ethanol-soaked samples is considerably lower compared to the untreated (see Table 2). This is in agreement with a previous report by Ullah et al. where application of ethanol to melt-blown based masks was

explored (Ullah et al. 2020). According to Table 2, the filtration efficiency of ethanol treated masks reduced by 41.63% (p : 0.0005). In addition, the pressure drop increased by 4.33 Pa (p : 0.831). This indicates that, once a nanofiber-based N95 mask is soaked in ethanol, its breathability will reduce and it will fail to efficiently halt hazardous PM aerosols of 0.3 μm in diameter. This may be due to a sudden change in the surface tension of the nanofibers when the fibers absorb ethanol and then dry out (Nazeeri et al. 2020). As illustrated in Figure 4, nanofibers undergo a noticeable damage seen as large cavity formations due to laceration of nanofibers. This is also apparent in FESEM images shown in Figure 5a where fibers are disintegrated. This in fact explains lower filtration efficiency. On the other hand, ethanol can cause a swelling of the PA6 layer (Heffernan et al. 2013; Geens, Van der Bruggen, and Vandecasteele 2004) which forces pores to tighten in the microstructure and give rise to a pressure drop across the layer. However, it is likely that the main contributing factor for reduced breathability is the swelling of the nonwoven fabric by ethanol (Nazeeri et al. 2020). This fabric is often made out of polypropylene (PP) and once swollen, a

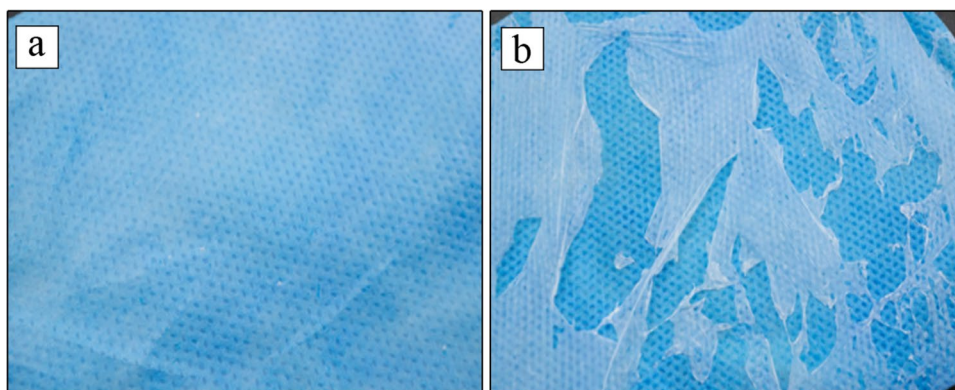
Table 2 Pressure Drop and Filtration efficiency before and after treatments.

| | Pressure Drop (Pa) @ 85 L.min ⁻¹ | | | Filtration Efficiency (%) for PM = 0.3 μm | | |
|---------------|--|-----------------|-----------------|---|-----------------|-----------------|
| | Before Treatment | After Treatment | <i>p</i> -value | Before Treatment | After Treatment | <i>p</i> -value |
| Ethanol (70%) | 158 | 162.33 | 0.831 | 98.96% | 57.33% | 0.0005 |
| Bleaching | 121.33 | 108.33 | 0.313 | 94.7% | 89.2% | 0.043 |
| Boiling | 134 | 151.33 | 0.103 | 98.66% | 89% | 0.005 |
| Steam | 147.66 | 150.66 | 0.815 | 98% | 87% | 0.080 |
| Autoclave | 171 | 158 | 0.463 | 99.6% | 98% | 0.006 |
| Oven | 147.33 | 127.66 | 0.007 | 99.9% | 92.66% | 0.489 |
| Ironing | 165.66 | 153.33 | 0.197 | 99.3% | 98.33% | 0.097 |
| Microwave | 147.33 | 141.33 | 0.818 | 97% | 93.66% | 0.523 |
| UVGI | 165 | 159 | 0.188 | 98.66% | 98% | 0.373 |

PM: Particulate Matters (PM)

UVGI: Ultraviolet Germicidal Irradiation

Fig. 4 Conformation of nanofiber layer deposited on nonwoven fabric a) before and b) after being soaked in ethanol



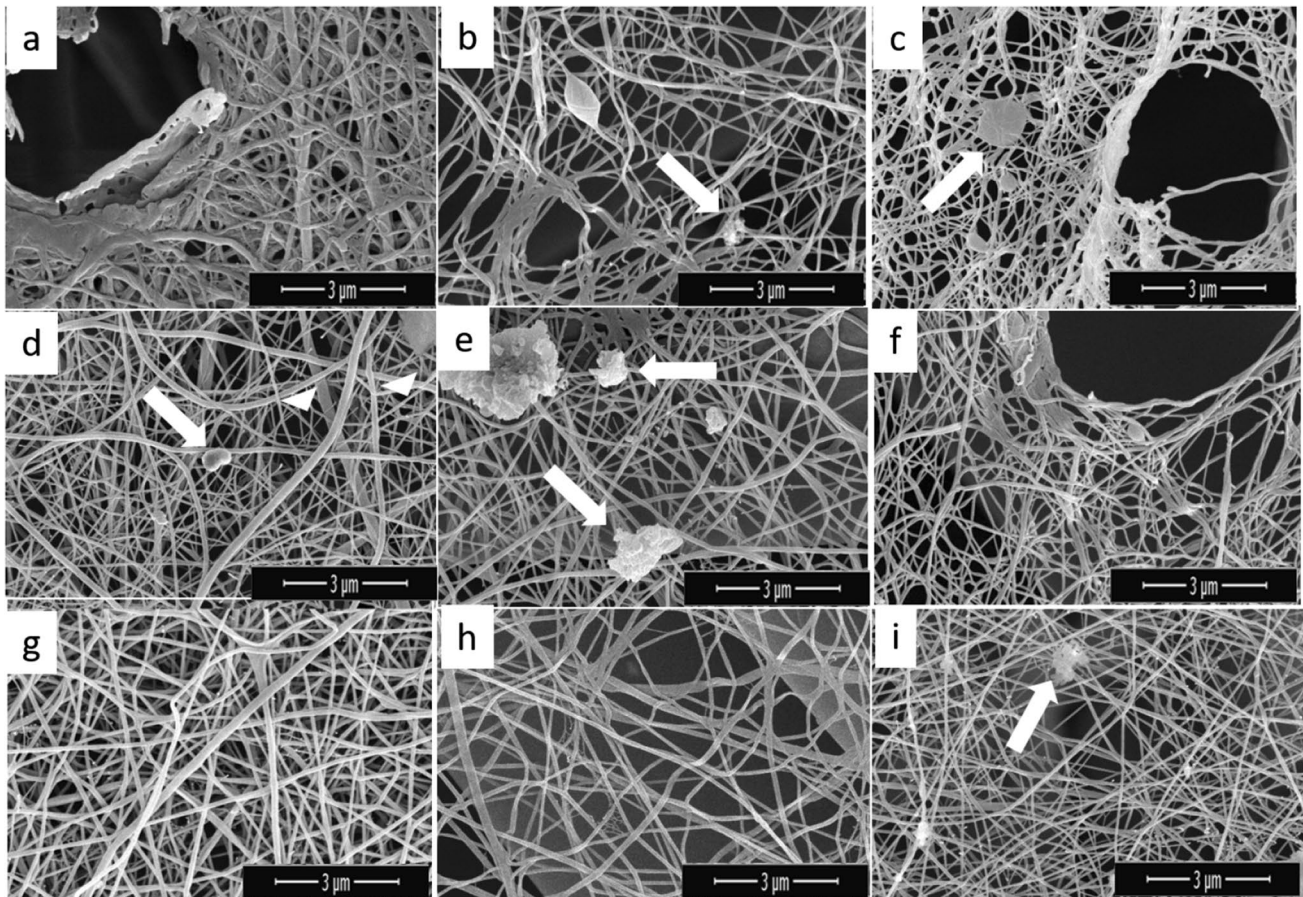


Fig. 5 FESEM images post application of a) 70% ethanol, b) bleach, c) boiling, d) steam, e) autoclave, f) static-air oven, g) conventional ironing, h) Microwave oven and i) Ultraviolet light. (13000X)

dense network with lower surface area is formed that limits air flow. Although, the swelling of fabrics is less evident in the case of polyethylene terephthalate/polyvinylidene difluoride (PET/PVDF) nanofibers, but it can nevertheless adversely affect filtration efficiency (Ullah et al. 2020).

Bleaching

Bleach is a 5–15% solution of sodium hypochlorite (NaOCl) which can act as an oxidizing agent against bacteria and viruses (Viscusi et al. 2009). According to Table 2, application of bleach on nanofiber-based masks caused a drop in filtration efficiency from approximately 95% to 89.2% (p : 0.043), but at the same time, it increased breathability, i.e. the pressure drop value decreased from 121 Pa to 108 Pa (p : 0.313). The sudden decrease in pressure can be an indication of damage to the consistency of the fibers along the substrate. It is suggested that when PA6 nanofibers are exposed to NaOCl, a reduction of amine groups (N-H) due to the presence of oxidative chlorine, leads to a cleavage of polyamide linkage (Simon and Nghiem 2014). As seen in

Figure 5b, this causes thinning of nanofibers and therefore formation of large pores within the membrane. The white arrow in this image marks a PM that has been trapped by the fibers

According to Viscusi et al., bleaching N95 masks by NaOCl for 30 minutes result in no significant change in the permeability of PM through the samples (Viscusi, King, and Shaffer 2007). Other groups have also reported minimum adverse effect on filtration efficiency of melt-blown based N95 masks after bleaching, however, persisting undesirable bleach odor post treatment has been apparent (Viscusi et al. 2009; Bergman et al. 2010). Therefore, while bleaching has not significantly affected filtration efficiency, concerns about toxic chemical residue and carcinogenic remains of bleach on the surface of the samples challenge the safety of this mode of decontamination.

Boiling

Boiling offers a simple alternative decontamination method that is accessible to most people (Gilbertson et al. 2020).

Based on the findings, the filtration efficiency of PA6 nanofiber-based masks following boiling reduced from 98.66% to 89% (p : 0.005) and the pressure drop increased from 134 to 151 Pa (p : 0.103). This may be due to the thinning of the nanofibers when exposed to heated water thus forming large pores and cavities (Figure 5c). The white arrow in this figure marks an abnormal solidification of PA6 polymer in the midst of the fibers. It is speculated that the resulting morphological change is due to the absorbance of water molecules by hydrophilic groups (-COOH, -NH₂ and -CO-NH-) available in PA6. This causes nanofibers to loosen their hydrogen bonds within their polymeric chains and dissolve (Tomara et al. 2019; Wevers et al. 2007; Razafimahefa et al. 2005). On the other hand, the hydrophobic part of PA6 (-CH₂-) results in partial aggregation of nanofibers (Razafimahefa et al. 2005). Similar studies suggest that while boiling does not alter the general appearance, filtration efficiency reduces and it is directly proportional to the number of heating cycles (Probst et al. 2020; Liao et al. 2020). Therefore, application of wet heat is generally not recommended to decontaminate N95 masks.

Steam

Application of heated steam is recommended by public health authorities to disinfect PPE against viruses (Yang and Wang 2020) and bacteria (Oztoprak, Kizilates, and Percin 2019). Interestingly, our findings indicate that while changes in pressure drop were not significant (p : 0.815), a meaningful reduction in filtration efficacy following steam exposure from 98% to 87% was apparent (p : 0.080). In the presence of water molecules, the electrical charges on the surface of nanofibers neutralizes thereby reducing filtration efficacy (Grinshpun, Yermakov, and Khodoun 2020). In addition, partial swelling due to the penetrating heated water molecules between nanofibers lead to an increase in diameter of nanofibers and a decrease in their surface area (see arrowhead in Figure 5d). This ultimately can result in a reduction of filtration efficiency (Wevers et al. 2007; Geens, Van der Bruggen, and Vandecasteele 2004).

Autoclave

The effectiveness of autoclave has been previously demonstrated by other studies as a decontamination method in laboratories and hospitals (Lin et al. 2018). In this method, unlike boiling and steam, a significant reduction in filtration efficiency was not evident (99.6% to 98%, p : 0.006). In addition, reduction in pressure drop post treatment was negligible (p : 0.463). Also, other than the loss of nanonets, no apparent change in the microstructure of the nanofibers that would alter filtration efficiency was detected (see Figure 5e).

However, it is reported that autoclaving common N95 masks in particular, reduces filtration efficiency due to the loss of electrical charge and damaged integrity (Grinshpun, Yermakov, and Khodoun 2020). While other studies support using autoclave for decontamination of masks (Harskamp et al. 2020). Our study supports the use of autoclaving for disinfecting PA6 nanofiber-based masks.

Dry Heat

Dry heat (oven) is known as an accessible decontamination method to inactivate viruses and bacteria (Tsai 2020; Rogers 2012). It has been reported that treatment with dry heat does not have a significant negative impact on filtration efficiency of common N95 masks (Fischer et al. 2020; Liao et al. 2020). In the following study, applying dry heat via an oven to decontaminate PA6 nanofibers-based masks led to a reduction in filtration efficiency (99.9% to 92.66%, p : 0.489) as well as a pressure drop (147 to 127 Pa, p : 0.007). In Figure 5f, a number of cavities with thick edges are observed across the membrane. Since the glass-transition temperature (T_g) of PA6 is 35–60°C (Maddah 2016; Guibo et al. 2013) and the disinfection of N95 masks in the oven occurs at 70°C, macromolecular movement increases and nanofibers stick together leading to cavity formation. In addition, some nanofibers increase in diameter at this temperature. Thus, reduction of efficiency and pressure drop after dry heat treatment may be due to the presence of these cavities.

Ironing

Among all potential decontamination methods, ironing is one of the most rapid and available methods to be used by the public. The effectiveness of ironing on inactivation of microorganisms and viruses has been reported by previous studies (Lakdawala et al. 2011; Rodriguez-Palacios et al. 2020). In our study, ironing did not significantly alter the filtration efficiency (99.3% to 98.33%, p : 0.097) or pressure drop (167 to 153 Pa, p : 0.197) of PA6 nanofibers. As seen in Figure 5g, ironing did not greatly alter the PA6 nanofiber membranes of masks but resulted in the disintegration of nanonets. Since the temperature of ironing was higher than the T_g of PA6, molecular movements are expected to lead to morphological changes. However, this does not actually happen due to the very short contact time with the mask. Although ironing does not significantly affect the microstructure of nanofibers, it may melt the PP spun bond (because of its T_m is 160–208 °C) (Maddah 2016) if the temperature is too high or ironed for too long. Therefore, this method largely depends on the individual using it.

Microwave

Microwave, which is presented as an electromagnetic wave in the frequency range of 300 MHz to 300 GHz, was presented as a technique for killing microorganisms in the mid-1980s. This technique relies on thermal energy to kill cells and microorganisms (Zhang et al. 2010). Microwave has been presented by different studies as a germicidal (Zhang et al. 2010) and virucidal (Woo et al. 2012) method to decontaminate masks for reuse when supply is short (for example, during the Covid-19 pandemic). We have shown that exposing PA6 nanofiber-based masks to microwave leads to a 3.33% reduction of filtration efficiency (from 97% to 93.66%, p : 0.523) along with a slight reduction in pressure drop (147 to 141 Pa, p : 0.818). In terms of macroscopic and microscopic features, no obvious changes are observed and nanofiber nanonets remain partly intact (Figure 5h).

Gertsman et al. (Gertsman et al. 2020) reported in a systematic review that microwave intervention in moist or dry conditions can decontaminate common N95 masks to be reused under NIOSH. However, Viscusi et al. have shown that decontaminating masks in dry microwave leads to melting (Viscusi et al. 2009; Viscusi, King, and Shaffer 2007). Others and we have shown that microwaving in a moist condition does not harm the mask structure and yields acceptable results in terms of filtration properties (Gertsman et al. 2020; Viscusi et al. 2011).

Ultraviolet

UVGI was previously confirmed to be an effective decontamination method against the influenza virus, H1N1 (Heimbuch et al. 2011; Mills et al. 2018), H5N1 (Lore et al. 2012), Covid-19 (Fischer et al. 2020), and bacteriophage MS2 (Fisher and Shaffer 2011) on masks (Yang et al. 2020; Anderson and Eng). Here, UVGI-treated PA6 nanofiber-based masks showed a 0.66% reduction in filtration efficiency (98.66% to 98.00%, p : 0.373) and a reduction in pressure drop (165 Pa to 159 Pa, p : 0.188) which are not significant. Microscopic features following UVGI treatment (Figure 5i) show thinner and partly broken up nanofibers as well as the absence of nanonets. However, the integrity of nanofiber membranes is preserved. The UVGI method was not destructive enough to reduce the filtration efficiency of PA6 nanofiber-based masks. However, previous work used FTIR characterization to show that longer exposure of PA6 nanofibers to UVGI can lead to an increase in the C=O peak of 1710 cm^{-1} which is related to oxidation and degradation of the nanofibers (Pinpathomrat, Yamada, and Yokoyama 2020). Therefore, at longer exposure times and repeated disinfection cycles, UVGI may damage the nanofibers by physical degradation (Tian et al. 2018; O'Hearn et al. 2020). In agreement with this finding, we show that applying UVGI

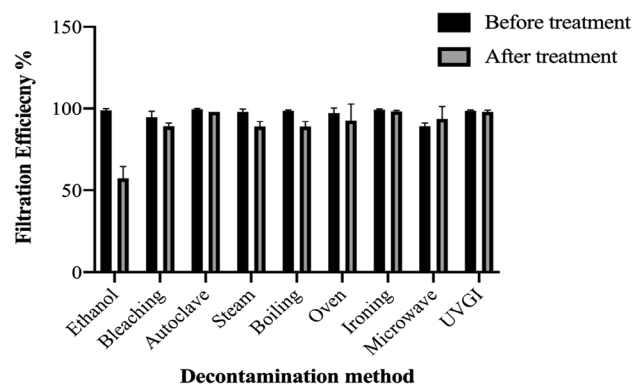


Fig. 6 Filtration efficiency before and after treatment

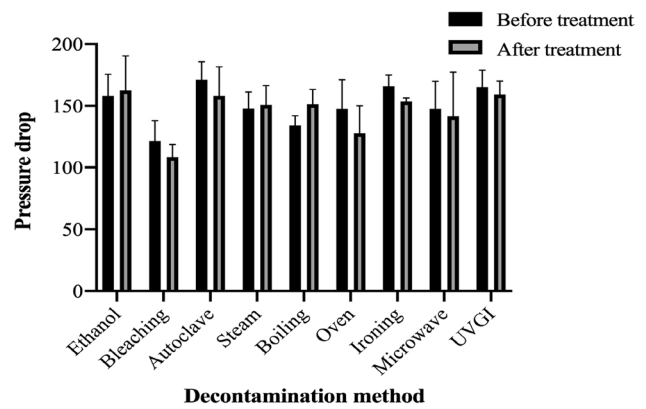


Fig. 7 Pressure drop before and after treatment

for one cycle (20 min) is not destructive in terms of filtration efficiency of PA6 nanofiber masks and can preserve the eligibility criteria of NIOSH. Similar results have been reported for N95 masks where UVGI does not affect the integrity, ability to filter aerosols, and ability to adapt to the face. In addition, it does not leave a smell or irritating/toxic residues. Finally, UVGI treatment of N95 masks does not create significant changes in appearance even when multiple disinfection cycles are performed (Salter et al. 2010; Bergman et al. 2010; Fischer et al. 2020; Liao et al. 2020; Fisher et al. 2009; Fisher and Shaffer 2011; Heimbuch et al. 2011; Viscusi et al. 2011; Lindsley et al. 2015; Lin et al. 2018).

Figures 6 and 7 illustrate changes in filtration efficiency and pressure drop before and after each decontamination method outlined above.

On the issue of PA6 nanofiber masks, investigations reveal that ethanol decontamination methods are not suitable because of a 42.66% reduction in filtration efficiency. In addition, concerns about odor and toxicity with bleaching make this method inappropriate. Boiling, steam, microwave and oven methods are associated with a reduction in filtration efficiency to 90%. Although ironing did not reduce

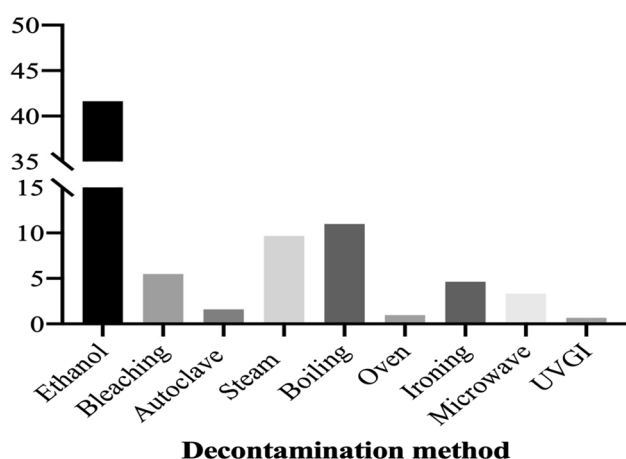


Fig. 8 Reduction of filtration efficiency after treatments

filtration efficiency significantly, it is not recommended as it is dependent on the individual and can melt PP. UVGI and autoclave are the best methods to disinfect PA6 nanofiber masks without changing the microstructure and filtration efficiency (Figure 8). Changes in pressure drop for all methods is not a criterion for NIOSH standards for N95 respirators (Figure 7). After decontamination, no apparent change in the visual appearance of the masks was detected.

Conclusion

The effects of various decontamination methods on the filtration performance and microstructural changes of PA6 nanofiber masks were evaluated. We found that alterations in microstructure of PA6 nanofibers imposed by each method is directly proportionate to changes in filtration efficiency. 70% ethanol causes a significant reduction (p : 0.2332) in filtration efficiency due to the deteriorative effects on nanofiber structure and is not recommended. Bleaching is not an appropriate disinfection method for masks due to concerns about odor and toxicity, although the reduction in filtration efficiency was not as much as that observed with ethanol. UVGI and autoclave treatments had small effects on the structure of nanofibers, which did not reduce filtration efficiency below 95% (respectively p : 0.008, 0.009). When disinfected with UVGI or autoclave, masks still meet N95 standards. Masks decontaminated via other methods described here had a filtration efficiency greater than 80% even though small changes in the nanofiber microstructure were observed. These masks are not qualified as N95. For all decontamination methods, changes in pressure drop are not determining, as it is not a rule out criteria for NIOSH standards for N95 respirators. It is important to note that the consumption of an unused mask instead of a decontaminated one, particularly for health workers who are in direct contact

with Covid-19 patients is rationally preferred. Nevertheless, this manuscript offers incites on various decontamination methods to help extend its usage should it become scarce.

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Faezeh Norouz: Manuscript writing and data analysis

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Declarations

Ethical approval No ethical approval was needed for this study.

Consent to participate Contribution of no participant was needed for this study.

Consent to publish All authors consent to publish the findings that are presented in this manuscript.

Competing interest Reza Faridi-Majidi, Raheleh Faridi-Majidi, and Safieh Boroumand are affiliated with Fanavaran Nano-Meghyas Co. that manufactures machinery for production of nanofiber-based media.

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