# 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 has caused shortage of PPE in many regions of the world. 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.


# Introduction

Face masks are among the most important personal protective equipment (PPE) that are proven to reduce transmission risks of infectious airborne particles (PaxtonForrestalDesselleKirraneSullivanPowell and Woodruff 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 (BałazyToivolaAdhikariSivasubramaniReponen and Grinshpun 2006). In a recent study by Haung et al., ‘increased availability of PPE’ ranks among the top four effective government intervention tactics to combat COVID-19 (HaugGeyrhoferLondeiDervicDesvars-LarriveLoretoPiniorThurner and Klimek 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, LiaoXiaoZhaoYuWangWangChu and Cui 2020). To respond to the current global needs, various studies have examined a number of decontamination techniques for the purpose of reusing masks (FischerMorrisvan DoremalenSarchetteMatsonBushmakerYindaSeifertGamble and Williamson 2020a, GrinshpunYermakov and Khodoun 2020, O'HearnGertsmanSampsonWebsterTsampalierosNgGibsonLobosAcharyaAgarwalBoggsChamberlainStaykovSikora and McNally 2020, ProbstGuerrerode Queiroz CardosoGrandeCrodaVenturinide Camargo FonsecaPaniago and Barreto 2020, Rubio-Romerodel Carmen Pardo-FerreiraGarcía and Calero-Castro 2020, ViscusiKing and Shaffer 2007, SmithHanselerWelleRattrayCampbellBrothertonMoudgilPackWegmann and Jensen 2020, FischerMorrisvan DoremalenSarchetteMatsonBushmakerYindaSeifertGamble and Williamson 2020b, LoreHeimbuchBrownWander and Hinrichs 2012, ViscusiBergmanEimer and Shaffer 2009, BergmanViscusiHeimbuchWanderSambol and Shaffer 2010, ViscusiBergmanNovakFaulknerPalmieroPowell and Shaffer 2011, GertsmanAgarwalO’HearnWebsterTsampalierosBarrowmanSampsonSikoraStaykov and Ng 2020, WooGrippinWu and Wander 2012, BoppBouyerGibbsNicholsNtiforo and Grimaldo 2020, LowePaladinoFarkeBoulterCawcuttEmodiGibbsHankinsHinkle and Micheels 2020, Juang and Tsai 2020, YangHuLi and Zhang 2020). While masks fabricated by the conventional melt-blown technique (SurekaGarg and Misra 2020) are the subject of these studies, with the advent of nanofiber technology and their use in production of masks (TebyetekerwaXuYang and Ramakrishna 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 travers 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 $L.min^{-1}$ must be blow 350 Pa (KondaPrakashMossSchmoldtGrant and Guha 2020). While conventional N95 masks based on melt-blown fabrication technique are arguably ineffective for particle size range of 0.1–0.3μm (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, ZhangLiuYuLuo and Ding 2016, WangZhaoWangPei and Li 2017). As seen in Fig. 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 (ZhuHanWangShaoXiongZhangPanYangSamal and Zhang 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.

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 *et al.* 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 | (LakdawalaPhamShah and Holton 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 | (ZhangDamitWelchParkWu and Sigmund 2010) |

*RT: Room Temperature

# 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 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

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). To evaluate filtration efficiency and pressure drop before and after treatment the PFE equipment is equipped with an opening area of 100 $cm^2$ at 85 $L.min^{-1}$.

## 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 ± 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, ChengWongChuangSoChenSridharToChanHung and Ho 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.* 2020a, Grinshpun *et al.* 2020, O'Hearn *et al.* 2020, Probst *et al.* 2020, Rubio-Romero *et al.* 2020, Viscusi *et al.* 2007, Smith *et al.* 2020, Fischer *et al.* 2020b, 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 *et al.* 2020, Tsai 2020b) have been the target of several decontamination studies (Fischer *et al.* 2020a, 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±43nm (see Figure 3b and 3c). The illustrated nanofiber layer with submicron pore size enables efficient filtration of particles larger than 0.3μm (PM 0.3μm). The ultrafine nanometer with the thickness of about 20 nm, formed within the nanofibrous structures that helps trap up to 95% of PM 0.3μm with a pressure drop range of 110-330 Pa (at 85 $L.min^{-1}$), which follows the standard NIOSH guidelines for N95 masks (Zhang *et al.* 2016).

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.

Table 2

Pressure Drop and Filtration efficiency before and after treatments.

# *Ethanol*

Expectedly, soaking samples in 70% ethanol has been shown effective for inactivation of viruses and bacteria situated on N95 masks (Fischer *et al.* 2020b, LinTangHungHua and Lai 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 (UllahUllahLeeJeongHashmiZhuJooCha and Kim 2020). According to Table 2, the filtration efficiency of ethanol treated masks reduced by 41.63% (p: 0.0005). In addition, the pressure

| | Pressure Drop (Pa) @ 85 $L.min^{-1}$ | | | Filtration Efficiency (%) for PM = 0.3 µm | | |
|---|---|---|---|---|---|---|
| | Before Treatment | After Treatment | p-value | Before Treatment | After Treatment | p-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

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 (NazeeriHilburnWuMohammedBadalChan and Kirschvink 2020a). 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 (HeffernanSemiãoDesmondCaoSafariHabimana and Casey 2013, GeensVan 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 (NazeeriHilburnWuMohammedBadalChan and Kirschvink 2020b). This fabric is often made out of polypropylene (PP) and once swollen, a 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 *et al.* 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 (GilbertsonQuintanar-SolaresLiland and Niermeyer 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, $-NH_2$ and -CO-NH-) available in PA6. This causes nanofibers to loosen their hydrogen bonds within their polymeric chains and dissolve (TomaraKarahaliouAnastassopoulosGeorgaKrontiras and Karger-Kocsis 2019, WeversMathotPijpersGoderis and Groeninckx 2007, RazafimahefaChlebickiVroman and Devaux 2005). On the other hand, the hydrophobic part of PA6 ($-(CH_2)_5-$) 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 (OztoprakKizilates 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 *et al.* 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 *et al.* 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 *et al.* 2020). While other studies support using autoclave for decontamination of masks (Harskampvan StratenBoumanvan Maltha-van Santvoortvan den Dobbelsteenvan der Sijp and Horeman 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 2020a, 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.* 2020a, 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, GuiboQingYahongYin and Yumin 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-PalaciosCominelliBassonPizarro and Ilic 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 $T_m$ is160-208 °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 *et al.* 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 (HeimbuchWallaceKinneyLumleyWuWoo and Wander 2011, MillsHarnishLawrenceSandoval-Powers and Heimbuch 2018), H5N1 (Lore *et al.* 2012), Covid-19 (Fischer *et al.* 2020a), 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 (PinpathomratYamada and Yokoyama 2020). Therefore, at longer exposure times and repeated disinfection cycles, UVGI may damage the nanofibers by physical degradation (TianWangQuWangZhuZhang and Liu 2018, O'Hearn *et al.* 2020). In agreement with this finding, we show that applying UVGI 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 (SalterKinneyWallaceLumleyHeimbuch and Wander 2010, Bergman *et al.* 2010, Fischer *et al.* 2020a, Liao *et al.* 2020, FisherRengasamyViscusiVo and Shaffer 2009, Fisher and Shaffer 2011, Heimbuch *et al.* 2011, Viscusi *et al.* 2011, LindsleyMartin JrThewlisSarkisianNwokoMead and Noti 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 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 (Figure7).

## 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 recommenced. 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.

## 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.

# Authors Contributions

Reza Faridi-Majidi: Project supervisor and funding

Seyed Nasrollah Tabatabei: Experimental design and manuscript editing

Raheleh Faridi-Majidi: Methodology and manuscript preparation

Faezeh Norouz: Manuscript writing and data analysis

Safieh Boroumand: Manuscript writing

# 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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# Availability and material

All the data and material pertinent to this manuscript are included and have been reviewed by all authors.

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## References

1. Anderson WA, Eng P UV Disinfection of N95 Filtering Facepiece Respirators: A Brief Review
2. Bałazy A, Toivola M, Adhikari A, Sivasubramani SK, Reponen T, Grinshpun SA (2006) Do N95 respirators provide 95% protection level against airborne viruses, and how adequate are surgical masks? Am J Infect Control 34:51–57
3. Bergman MS, Viscusi DJ, Heimbuch BK, Wander JD, Sambol AR, Shaffer RE (2010) Evaluation of multiple (3-cycle) decontamination processing for filtering facepiece respirators. J Eng Fibers Fabr 5:155892501000500405
4. Bopp NE, Bouyer DH, Gibbs CM, Nichols JE, Ntiforo CA, Grimaldo MA (2020) Multicycle Autoclave Decontamination of N95 Filtering Facepiece Respirators. *Applied Biosafety*, 1535676020924171
5. Cheng VC, Wong S-C, Chuang VW, So SY, Chen JH, Sridhar S, To KK, Chan JF, Hung IF, Ho P-L (2020) The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2. *Journal of Infection*
6. Fennelly KP (2020) Particle sizes of infectious aerosols: implications for infection control. *The Lancet Respiratory Medicine*
7. Fischer RJ, Morris DH, Van Doremalen N, Sarchette S, Matson MJ, Bushmaker T, Yinda CK, Seifert SN, Gamble A, Williamson BN (2020a) Assessment of N95 respirator decontamination and re-use for SARS-CoV-2. *MedRxiv*
8. Fischer RJ, Morris DH, Van Doremalen N, Sarchette S, Matson MJ, Bushmaker T, Yinda CK, Seifert SN, Gamble A, Williamson BN (2020b) Effectiveness of N95 respirator decontamination and reuse against SARS-CoV-2 virus. Emerg Infect Dis 26:2253
9. Fisher E, Rengasamy S, Viscusi D, Vo E, Shaffer R (2009) Development of a test system to apply virus-containing particles to filtering facepiece respirators for the evaluation of decontamination procedures. Appl Environ Microbiol 75:1500–1507
10. Fisher EM, Shaffer RE (2011) A method to determine the available UV-C dose for the decontamination of filtering facepiece respirators. J Appl Microbiol 110:287–295

11. Geens J, Van Der Bruggen B, Vandecasteele C (2004) Characterisation of the solvent stability of polymeric nanofiltration membranes by measurement of contact angles and swelling. Chem Eng Sci 59:1161–1164
12. Gertsman S, Agarwal A, O'hearn K, Webster R, Tsampalieros A, Barrowman N, Sampson M, Sikora L, Staykov E, Ng R (2020) Microwave-and heat-based decontamination of n95 filtering facepiece respirators: a systematic review. *Journal of Hospital Infection*
13. Gilbertson J, Quintanar-Solares M, Liland F, Niermeyer S (2020) High-Level Disinfection of Reusable Neonatal Resuscitation Equipment through Boiling and Steaming. *Journal of Hospital Infection*
14. Grinshpun SA, Yermakov M, Khodoun M (2020) Autoclave sterilization and ethanol treatment of re-used surgical masks and N95 respirators during COVID-19: impact on their performance and integrity. J Hosp Infect 105:608–614
15. Guibo Y, Qing Z, Yahong Z, Yin Y, Yumin Y (2013) The electrospun polyamide 6 nanofiber membranes used as high efficiency filter materials: Filtration potential, thermal treatment, and their continuous production. J Appl Polym Sci 128:1061–1069
16. Harskamp RE, Van Straten B, Bouman J, Van Maltha-Van Santvoort B, Van Den Dobbelsteen JJ, Van Der Sijp JR, Horeman T (2020) Reprocessing filtering facepiece respirators in primary care using medical autoclave: prospective, bench-to-bedside, single-centre study. BMJ open 10:e039454
17. Haug N, Geyrhofer L, Londei A, Dervic E, Desvars-Larrive A, Loreto V, Pinior B, Thurner S, Klimek P (2020) Ranking the effectiveness of worldwide COVID-19 government interventions. *Nature human behaviour*, 1–10
18. Heffernan R, Semião A, Desmond P, Cao H, Safari A, Habimana O, Casey E (2013) Disinfection of a polyamide nanofiltration membrane using ethanol. J Membr Sci 448:170–179
19. Heimbuch BK, Wallace WH, Kinney K, Lumley AE, Wu C-Y, Woo M-H, Wander JD (2011) A pandemic influenza preparedness study: use of energetic methods to decontaminate filtering facepiece respirators contaminated with H1N1 aerosols and droplets. Am J Infect Control 39:e1–e9
20. Juang PS, Tsai P (2020) N95 Respirator Cleaning and Reuse Methods Proposed by the Inventor of the N95 Mask Material. *Journal of Emergency Medicine*
21. Konda A, Prakash A, Moss G, Schmoldt M, Grant G, Guha S (2020) Correction to Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks. ACS Nano 14:10742–10743
22. Lakdawala N, Pham J, Shah M, Holton J (2011) Effectiveness of low-temperature domestic laundry on the decontamination of healthcare workers' uniforms. Infection Control Hospital Epidemiology 32:1103–1108
23. Leung WWF, Sun Q (2020) Electrostatic charged nanofiber filter for filtering airborne novel coronavirus (COVID-19) and nano-aerosols. *Separation and Purification Technology*, 116886
24. Liao L, Xiao W, Zhao M, Yu X, Wang H, Wang Q, Chu S, Cui Y (2020) Can N95 respirators be reused after disinfection? How many times? *ACS nano*
25. Lin TH, Tang FC, Hung PC, Hua ZC, Lai CY (2018) Relative survival of Bacillus subtilis spores loaded on filtering facepiece respirators after five decontamination methods. Indoor air 28:754–762
26. Lindsley WG, Martin SB Jr, Thewlis RE, Sarkisian K, Nwoko JO, Mead KR, Noti JD (2015) Effects of ultraviolet germicidal irradiation (UVGI) on N95 respirator filtration performance and structural integrity. J Occup Environ Hyg 12:509–517
27. Lore MB, Heimbuch BK, Brown TL, Wander JD, Hinrichs SH (2012) Effectiveness of three decontamination treatments against influenza virus applied to filtering facepiece respirators. Annals of occupational hygiene 56:92–101

28. Lowe JJ, Paladino KD, Farke JD, Boulter K, Cawcutt K, Emodi M, Gibbs S, Hankins R, Hinkle L, Micheels T (2020) N95 filtering facepiece respirator ultraviolet germicidal irradiation (UVGI) process for decontamination and reuse. *Nebraska Medicine*
29. Mackenzie D (2020) Reuse of N95 masks. *Engineering (Beijing, China)*
30. Maddah HA (2016) Polypropylene as a promising plastic: A review. Am J Polym Sci 6:1–11
31. Mills D, Harnish DA, Lawrence C, Sandoval-Powers M, Heimbuch BK (2018) Ultraviolet germicidal irradiation of influenza-contaminated N95 filtering facepiece respirators. Am J Infect Control 46:e49–e55
32. Nazeeri AI, Hilburn IA, Wu D-A, Mohammed KA, Badal DY, Chan MH, Kirschvink JL (2020a) An Efficient Ethanol-Vacuum Method for the Decontamination and Restoration of Polypropylene Microfiber N95 Medical Masks & Respirators. In. Posted April
33. Nazeeri AI, Hilburn IA, Wu D-A, Mohammed KA, Badal DY, Chan MH, Kirschvink JL (2020b) Ethanol-Drying Regeneration of N95 Respirators. *medRxiv*
34. O'hearn K, Gertsman S, Sampson M, Webster R, Tsampalieros A, Ng R, Gibson J, Lobos AT, Acharya N, Agarwal A, Boggs S, Chamberlain G, Staykov E, Sikora L, Mcnally JD (2020) Decontaminating N95 and SN95 masks with ultraviolet germicidal irradiation does not impair mask efficacy and safety. J Hosp Infect 106:163–175
35. Organization WH (2020) Advice on the use of masks in the context of COVID-19: interim guidance, 5 June 2020. In. World Health Organization
36. Oztoprak N, Kizilates F, Percin D (2019) Comparison of steam technology and a two-step cleaning (water/detergent) and disinfecting (1,000 resp. 5,000 ppm hypochlorite) method using microfiber cloth for environmental control of multidrug-resistant organisms in an intensive care unit. *GMS Hygiene and Infection Control*, 14
37. Paxton NC, Forrestal DP, Desselle M, Kirrane M, Sullivan C, Powell SK, Woodruff MA (2020) N95 Respiratory Masks for COVID-19: A Review of the Literature to Inform Local Responses to Global Shortages
38. Pinpathomrat B, Yamada K, Yokoyama A (2020) The effect of UV irradiation on polyamide 6/carbon-fiber composites based on three-dimensional printing. SN Applied Sciences 2:1–9
39. Probst LF, Guerrero ATG, De Queiroz Cardoso AI, Grande AJ, Croda MG, Venturini J, De Camargo Fonseca MC, Paniago AMM, Barreto JOM (2020) Decontamination Methods for Respiratory Protection Mask Model N95: A Rapid Review
40. Razafimahefa L, Chlebicki S, Vroman I, Devaux E (2005) Effect of nanoclay on the dyeing ability of PA6 nanocomposite fibers. Dyes pigments 66:55–60
41. Rodriguez-Palacios A, Cominelli F, Basson AR, Pizarro TT, Ilic S (2020) Textile Masks and Surface Covers—A Spray Simulation Method and a "Universal Droplet Reduction Model" Against Respiratory Pandemics. Frontiers in Medicine 7:260
42. Rogers W (2012) Steam and dry heat sterilization of biomaterials and medical devices. In: Sterilisation of Biomaterials and Medical Devices. Elsevier, pp 20–55
43. Rubio-Romero JC, Del Carmen Pardo-Ferreira M, García JaT, Calero-Castro S (2020) Disposable masks: Disinfection and sterilization for reuse, and non-certified manufacturing, in the face of shortages during the COVID-19 pandemic. *Safety Science*, 104830
44. Salter W, Kinney K, Wallace W, Lumley A, Heimbuch B, Wander J (2010) Analysis of residual chemicals on filtering facepiece respirators after decontamination. J Occup Environ Hyg 7:437–445

45. Simon AR, Nghiem LD (2014) Effects of hypochlorite exposure on morphology and trace organic contaminant rejection by NF/RO membranes
46. Smith JS, Hanseler H, Welle J, Rattray R, Campbell M, Brotherton T, Moudgil T, Pack TF, Wegmann K, Jensen S (2020) Effect of various decontamination procedures on disposable N95 mask integrity and SARS-CoV-2 infectivity. *Journal of Clinical and Translational Science*, 1–14
47. Sureka B, Garg MK, Misra S (2020) N95 respirator and surgical mask in the pandemic of COVID-19. Annals of Thoracic Medicine 15:247
48. Tebyetekerwa M, Xu Z, Yang S, Ramakrishna S (2020) Electrospun nanofibers-based face masks. Advanced Fiber Materials 2:161–166
49. Tian M, Wang Z, Qu L, Wang K, Zhu S, Zhang X, Liu R (2018) Enhanced UV photo-stabilization of Nylon 6 filament with reduced graphene oxide/polyurethane nanocomposite Inks. *International Journal of Clothing Science and Technology*
50. Tomara GN, Karahaliou PK, Anastassopoulos DL, Georga SN, Krontiras CA, Karger-Kocsis J (2019) Effect of moisture and filler content on the structural, thermal and dielectric properties of polyamide-6/boehmite alumina nanocomposites. Polym Int 68:871–885
51. Tsai P (2020a) Performance of masks and discussion of the inactivation of SARS-CoV-2. Engineered Science 10:1–7
52. Tsai P (2020b) Performance of masks and discussion of the inactivation of SARS-CoV-2. Engineered Science 10:1–7
53. Ullah S, Ullah A, Lee J, Jeong Y, Hashmi M, Zhu C, Joo KI, Cha HJ, Kim IS (2020) Reusability comparison of melt-blown vs nanofiber face mask filters for use in the coronavirus pandemic. ACS Applied Nano Materials 3:7231–7241
54. Viscusi DJ, Bergman MS, Eimer BC, Shaffer RE (2009) Evaluation of five decontamination methods for filtering facepiece respirators. Annals of occupational hygiene 53:815–827
55. Viscusi DJ, Bergman MS, Novak DA, Faulkner KA, Palmiero A, Powell J, Shaffer RE (2011) Impact of three biological decontamination methods on filtering facepiece respirator fit, odor, comfort, and donning ease. J Occup Environ Hyg 8:426–436
56. Viscusi DJ, King WP, Shaffer RE (2007) Effect of decontamination on the filtration efficiency of two filtering facepiece respirator models. Journal-International Society for Respiratory Protection 24:93
57. Wang J, Zhao W, Wang B, Pei G, Li C (2017) Multilevel-layer-structured polyamide 6/poly (trimethylene terephthalate) nanofibrous membranes for low-pressure air filtration. *Journal of Applied Polymer Science*, 134
58. Wevers MG, Mathot VB, Pijpers TF, Goderis B, Groeninckx G (2007) Full dissolution and crystallization of polyamide 6 and polyamide 4.6 in water and ethanol. In: Progress in Understanding of Polymer Crystallization. Springer, pp 151–168
59. Woo M-H, Grippin A, Wu C-Y, Wander J (2012) Microwave-irradiation-assisted HVAC filtration for inactivation of viral aerosols. Aerosol Air Quality Research 12:295–303
60. Yang H, Hu J, Li P, Zhang C (2020) Ultraviolet germicidal irradiation for filtering facepiece respirators disinfection to facilitate reuse during COVID-19 pandemic: A review. *Photodiagnosis and photodynamic therapy*, 101943
61. Yang P, Wang X (2020) COVID-19: a new challenge for human beings. Cell Mol Immunol 17:555–557

62. Zhang Q, Damit B, Welch J, Park H, Wu C-Y, Sigmund W (2010) Microwave assisted nanofibrous air filtration for disinfection of bioaerosols. J Aerosol Sci 41:880–888
63. Zhang S, Liu H, Yu J, Luo W, Ding B (2016) Microwave structured polyamide-6 nanofiber/net membrane with embedded poly (m-phenylene isophthalamide) staple fibers for effective ultrafine particle filtration. Journal of Materials Chemistry A 4:6149–6157
64. Zhu M, Han J, Wang F, Shao W, Xiong R, Zhang Q, Pan H, Yang Y, Samal SK, Zhang F (2017) Electrospun nanofibers membranes for effective air filtration. Macromol Mater Eng 302:1600353

# Figures

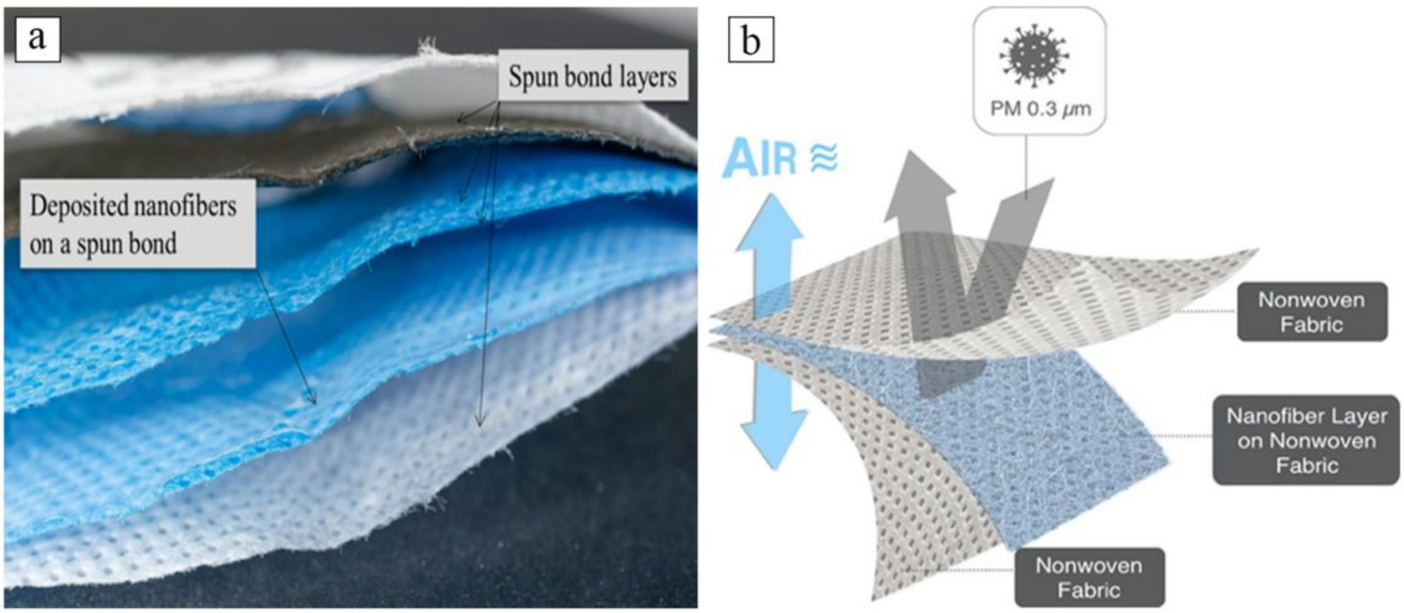
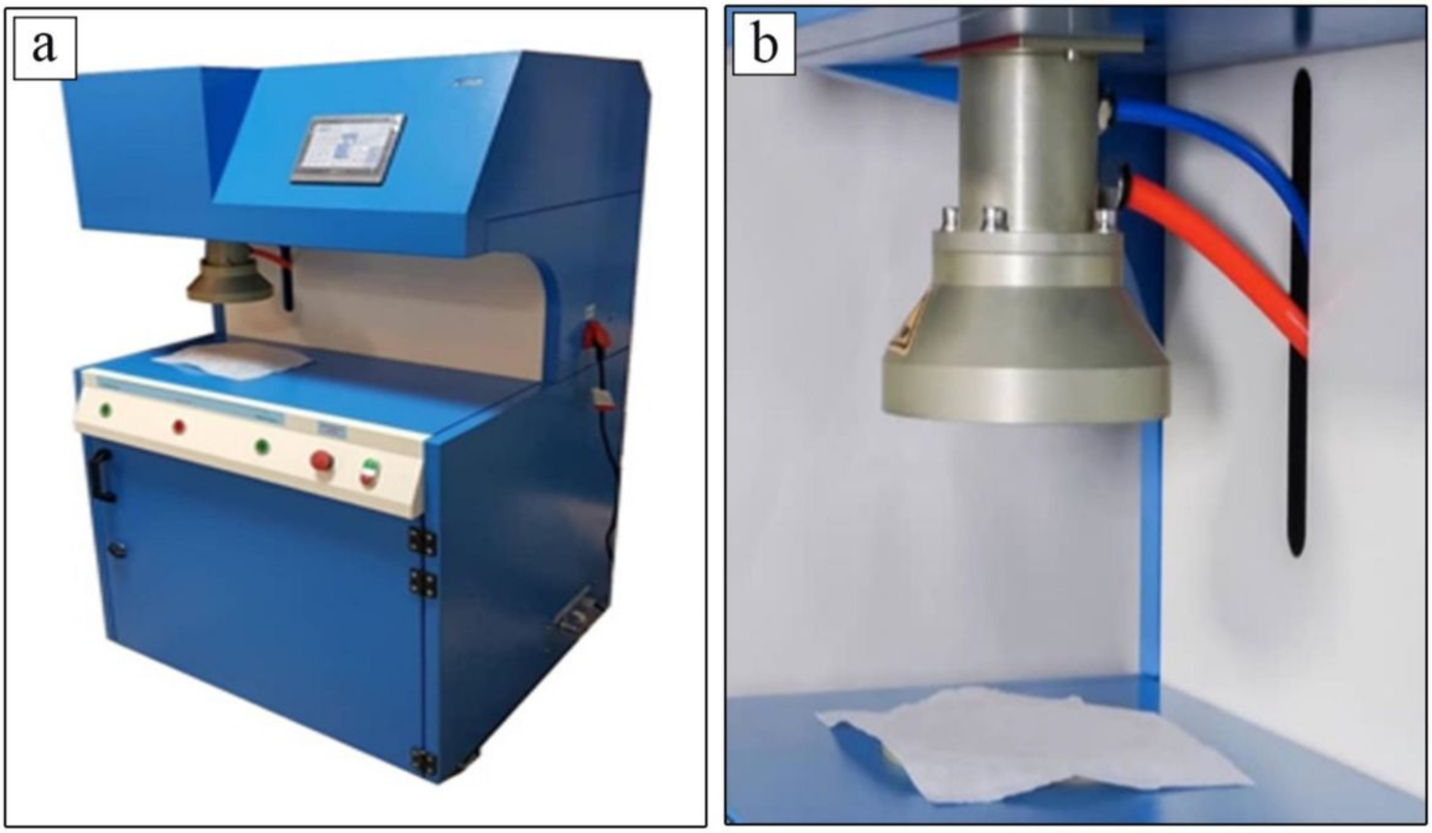


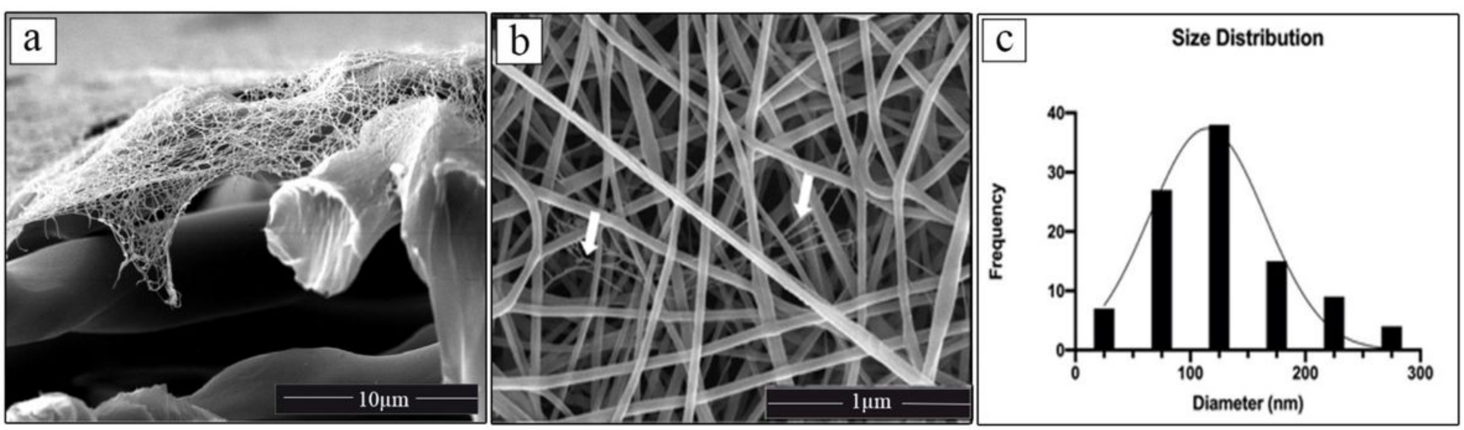

**Figure 1**

Structural layers of a nanofiber-based mask




#### Figure 2

Particle Filtration Efficiency equipment to evaluate filtration efficiency




#### Figure 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.

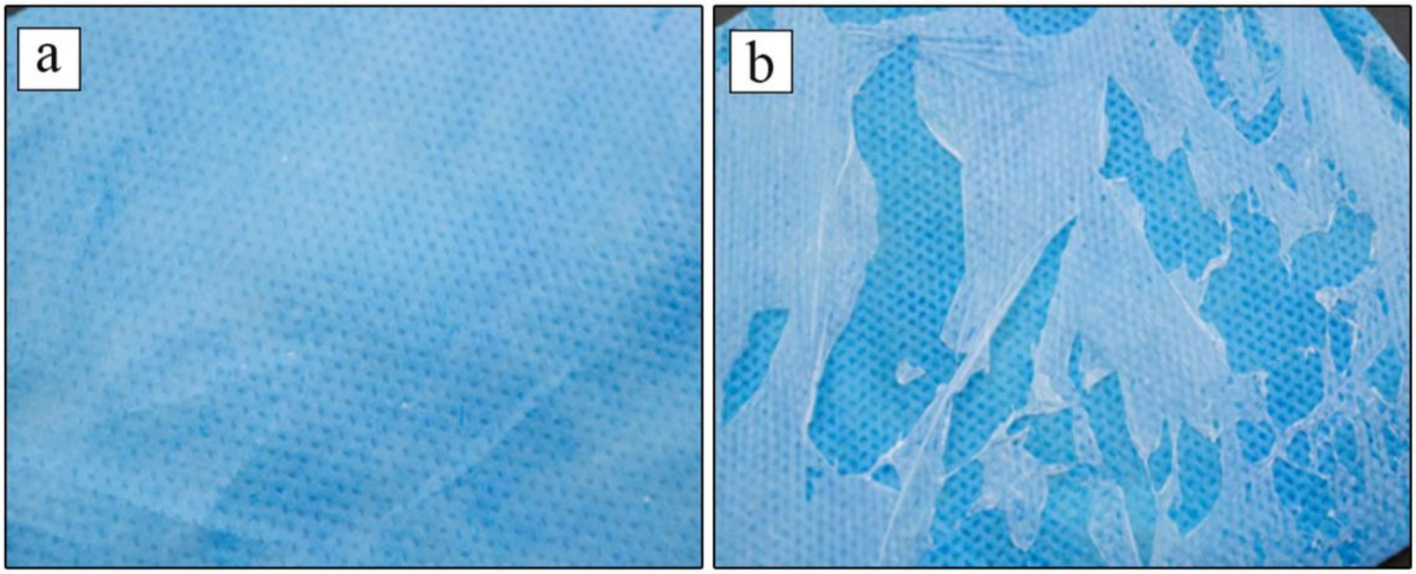



**Figure 4**

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

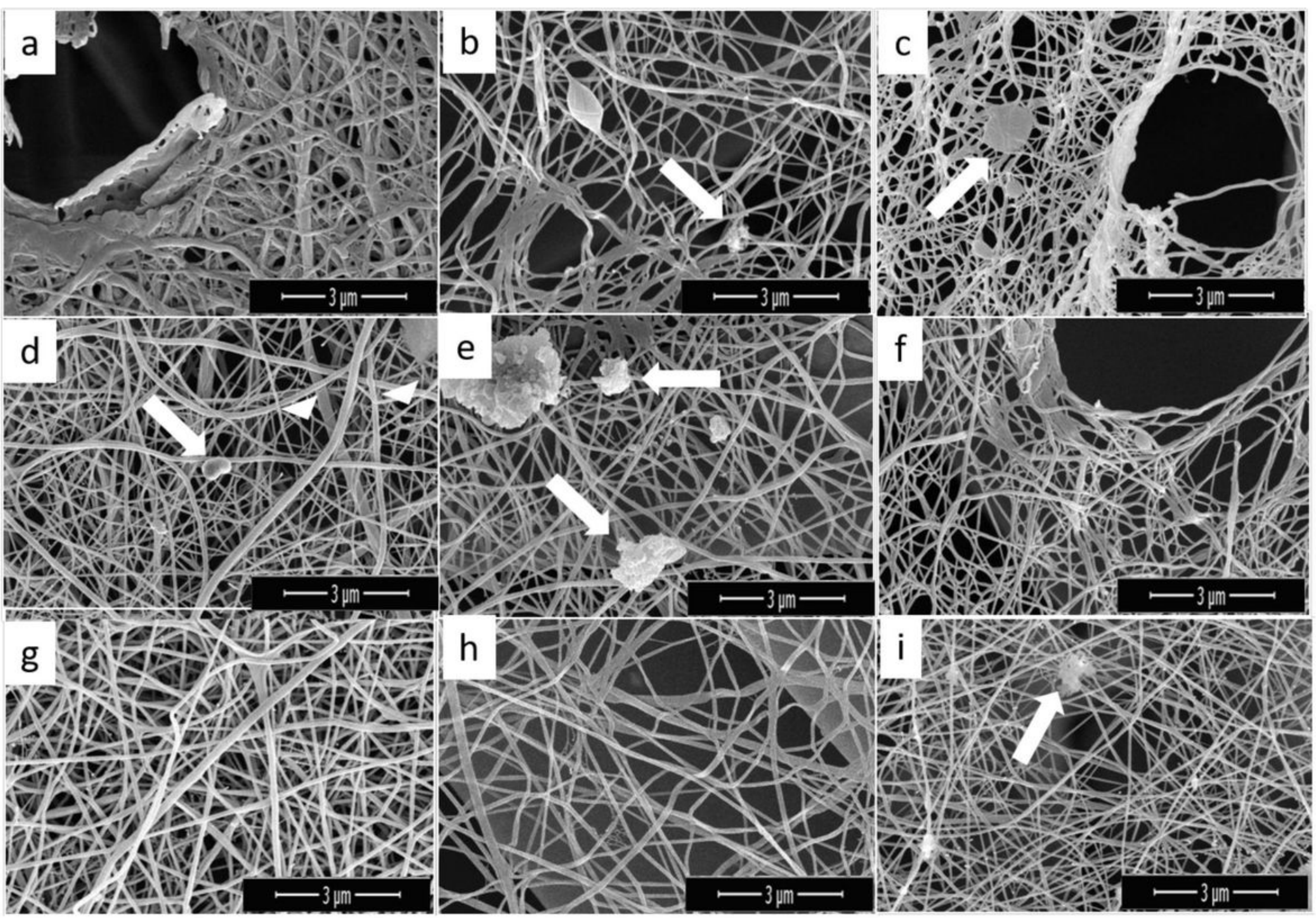
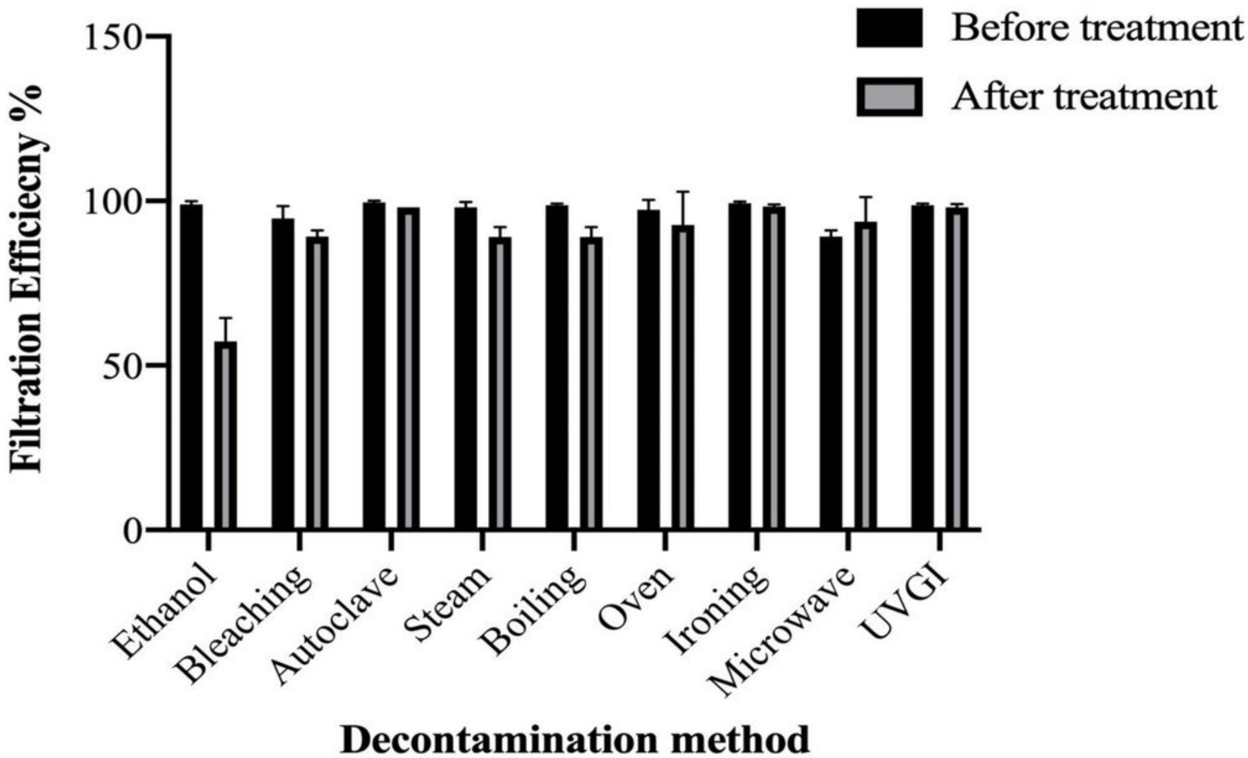


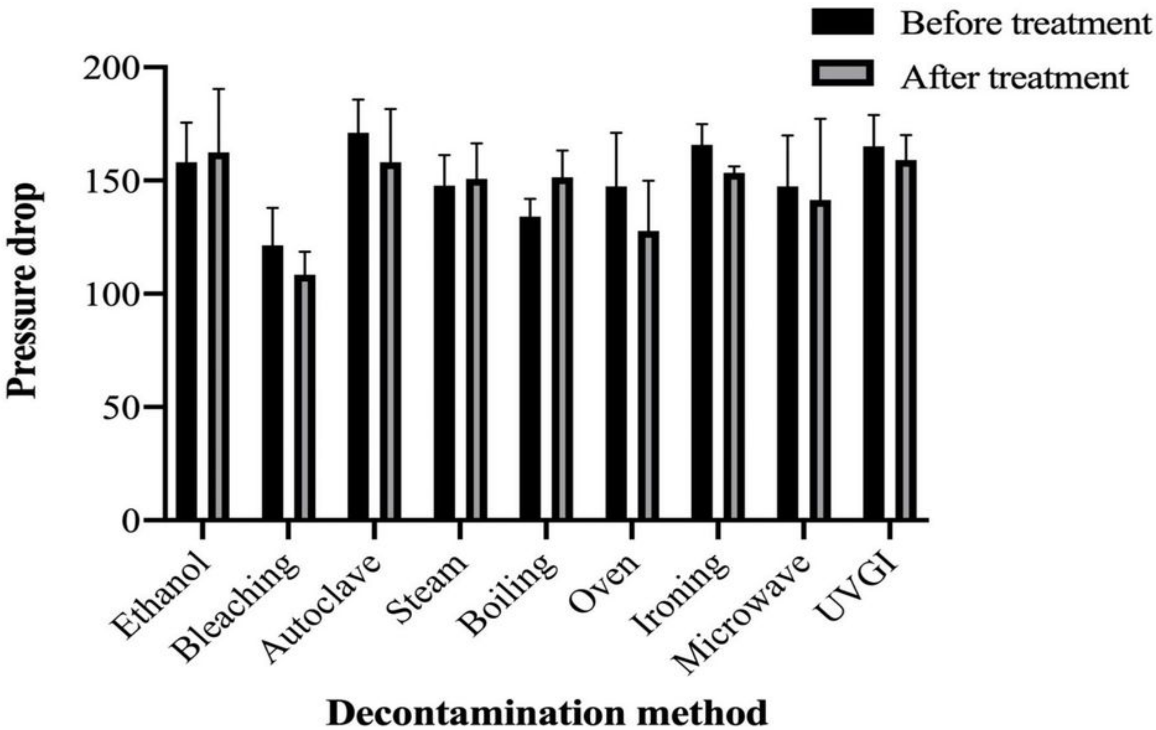

**Figure 5**

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)




## Figure 6

Filtration efficiency before and after treatment




## Figure 7

Pressure drop before and after treatment

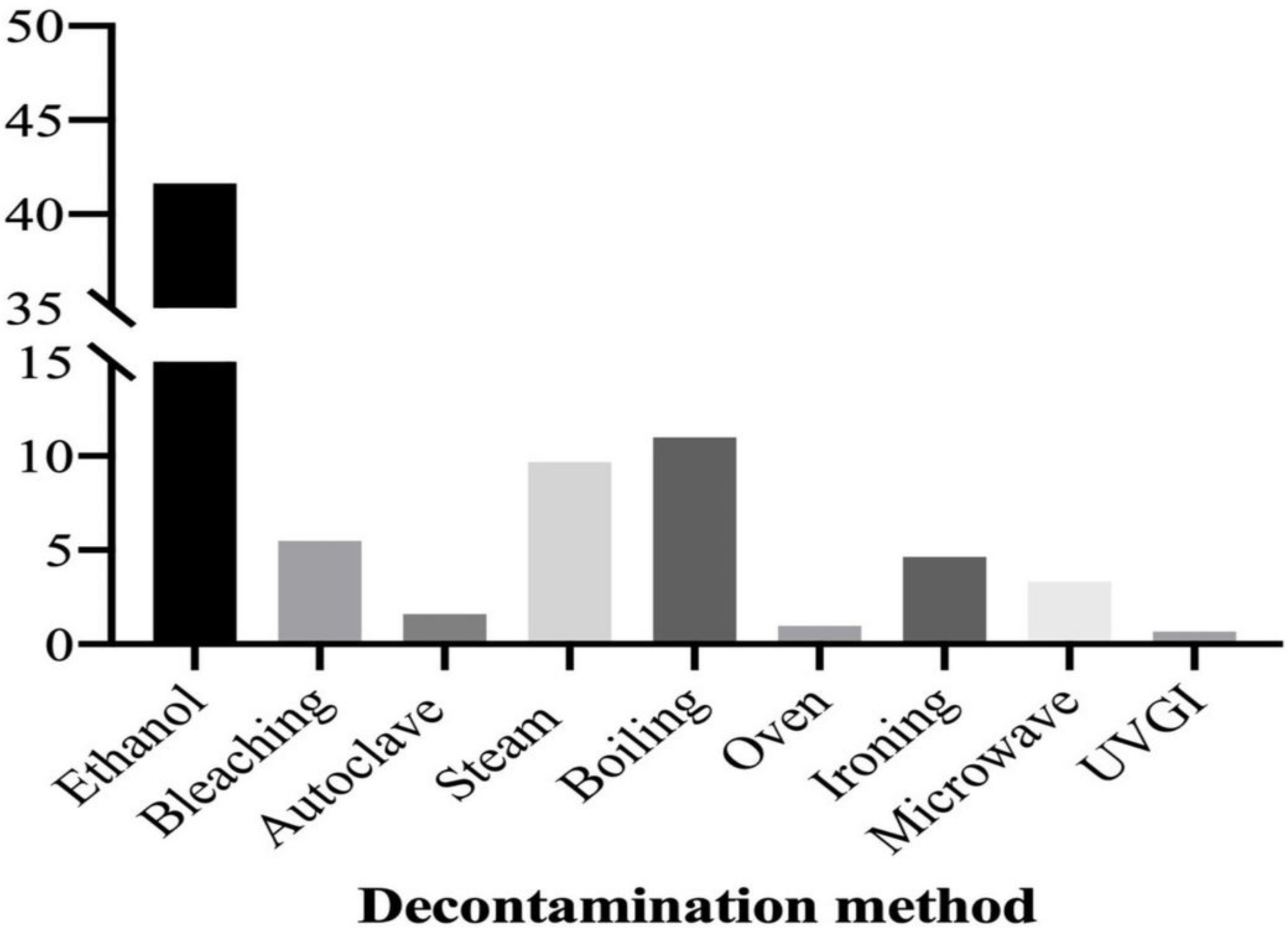



**Figure 8**

Reduction of filtration efficiency after treatments