Germicidal Ultraviolet Light Does Not Damage or Impede Performance of N95 Masks Upon Multiple Uses

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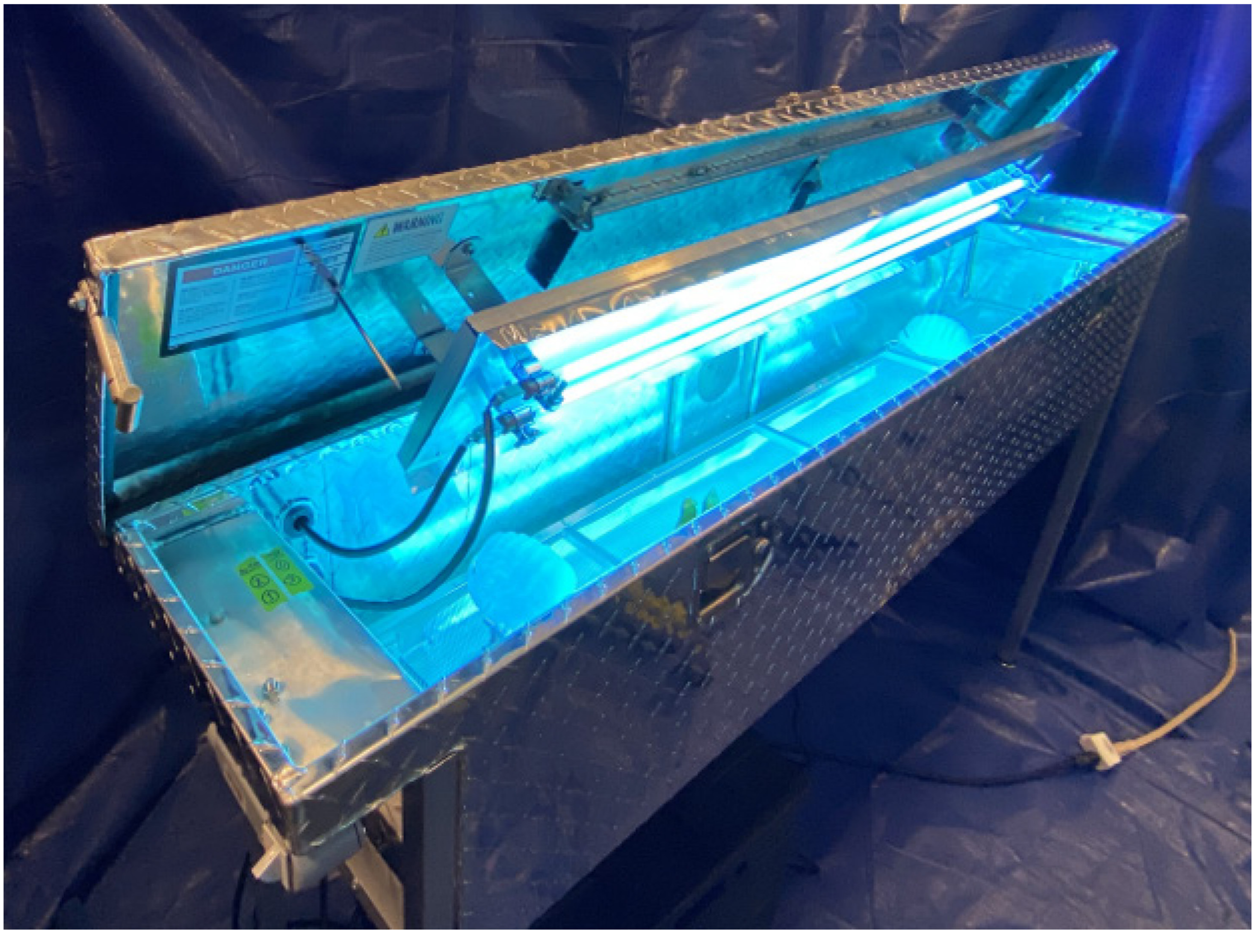

Abstract

The COVID-19 pandemic is increasing the need for personal protective equipment (PPE) worldwide, including the demand for facial masks used by healthcare workers. Disinfecting and reusing these masks may offer benefits in the short-term to meet urgent demand. Germicidal ultraviolet light provides a non-chemical, easily deployable technology capable of achieving inactivation of H1N1 virus on masks. Working with N95-rated masks and non-rated surgical masks, we demonstrated that neither 254 nor 265nm UV-C irradiation at 1 and 10 J/cm^2 had adverse effects on the masks' ability to remove aerosolized virus-sized particles. Additional testing showed no change in polymer structure, morphology, or surface hydrophobicity for multiple layers in the masks and no change in pressure drop or tensile strength of the mask materials. Results were similar when applying 254nm low-pressure UV lamps and 265nm light emitting diodes. Based on the input from healthcare workers and our findings, a treatment system and operational manual were prepared to enable treatment and reuse of N95 facial masks. Knowledge gained during this study can inform techno-economic analyses for treating and reusing masks or lifecycle assessments of options to reduce the enormous waste production of single-use PPE used in the healthcare system, especially during pandemics.

Introduction

Personal protective equipment (PPE) rose to the forefront of global concern during the recent COVID-19 pandemic. However, while the single-use of PPE has been a common practice to maximize protection of healthcare workers and patients, it generates large tonnage and volumes of biomedical waste annually.[1] For example, the US alone uses 1.5 billion N95 respiratory facial masks per year.[2] Current disposal practices for biomedical waste, including facial masks, includes disinfection (e.g., injected with steam, shredded, heating to 200 °C in microwaves) and then placing in landfills. While shortages of PPE, including facial masks, have accelerated during the 2019/2020 pandemic caused by SARS-CoV-2, a longer-term strategy for on-site disinfection may allow safe reuse of PPE and provide a reliable disposal alternative, thereby reducing annual waste production.

Numerous disinfection strategies for facial masks have been proposed, but it wasn't until the middle of April 2020 that the Center for Disease Control and Prevention (CDC) provided guidelines for three processes targeting decontamination and reuse of filtering facepiece respirators (FFRs).[3] The CDC identified ultraviolet (UV) germicidal irradiation, vaporous hydrogen peroxide, and moist heat as the most promising methods to decontaminate FFRs. A a common feature of other disinfection treatments (e.g., liquid or aerosol hydrogen peroxide, autoclave-like treatments with moist air, and various gas treatments (e.g., ozone) [4-8]) is the need for chemical handling, air monitoring, and centralized treatment. In contrast, UV treatment offers a chemical-free strategy and could take less than 5 minutes to achieve.[9, 10] UV treatment can be performed anywhere power is available and can be scaled to treat different numbers of masks, and thus UV treatment is the focus of this paper.

Germicidal light in the UV-C range (100–280nm) disrupts DNA and RNA, forming pyrimidine dimers, thus inactivating viruses and other microorganisms.[11-14] Studies show > 99.9% inactivation for several influenza viruses and coronaviruses when applying UV dosages ranging from 0.5 to 1.8 J/cm^2.[6, 9, 10, 15-17] For a study with 15 different N95 masks that were soiled with H1N1 influenza virus, 1 J/cm^2 UV dose incident on the fabric achieved over 3-log reduction in recoverable virus.[16, 18] On other surfaces, much lower UV-C dosages (< 50 mJ/cm^2) are reported to inactivate similar virus types.[17] While most studies evaluated UV treatment's ability to disinfect masks, there is a paucity of information about impacts of UV treatment on polymer properties (chemistry, structure) that influence removal of aerosolized particles during reuse. Therefore, with the eventual aim of understanding the viability of safely reusing facial masks, this paper first quantified the ability of masks to remove virus-sized aerosol particles and then characterized potential detrimental impacts of UV-C exposure on representative N95 and surgical mask material physical and chemical properties (e.g., polymer structure, morphology, surface contact angle). Second, to design and fabricate reactors suitable to irradiate facial masks, we compared commonly-used UV-C light sources (254nm from UV low-pressure mercury lamps as well as 265nm from light emitting diodes (LEDs)) to provide equivalent UV-C dosages to masks. Light source selection and final reactor design is considered based on the comparison results for time to achieve target UV dosage and cost. The exposure dose in this study ranged from 1 – 10 J/cm^2 to account for CDC recommendation for irradiation dose (1J/cm^2) and potential multiple treatment cycles. It should be noted that the 1 J/cm^2 is at the high end of UV dosages recommended, and is much higher than reported UV dosages required for coronavirus inactivation in water.[17] This paper is not intended to quantify the safety of masks or the ability of UV light to disinfect used masks, but is intended to understand how reported ranges of UV-C dosages required for coronavirus inactivation potentially impact facial mask material properties and performance to remove aerosolized virus-sized particles. Findings from this study contribute to developing shorter-term strategies to safely reuse PPE materials that are in limited supply during pandemics and also provide longer-term strategies to reuse PPE materials with the intended aim of reducing PPE biohazard waste and disposal.

Materials and Methods

Figure 1 shows three facial masks containing different polymers: 1) surgical mask (47567, O&M Halyard, Inc., GA); 2) N95 Mask A (1860 N95, 3M, MN); and 3) N95 Mask B (1500 N95, Moldex, CA). The two N95 mask brands were selected because a prior study showed the ability to disinfect influenza virus on the masks with 1 J/cm^2.[16]. Following approaches previously applied during UV irradiation mask testing,[7] coupons of the masks (4cm *x* 4cm) were used for physicochemical characterization and aerosol challenge tests; the thickness of the coupons was identical with the as-received new masks.

Two UV exposure apparatuses—a collimated beam reactor equipped with 265nm LEDs and a box reactor equipped with 254nm low pressure UV lamps—were used to irradiate mask coupons (Figure SI.1-2). UV dosages of zero (control) plus 1 and 10 J/cm^2 were selected based on ability to achieve >3 log (i.e., > 99.9%) inactivation of H1N1 influenza.[16] Irradiation experiments were conducted in triplicate on separate coupons. Safety warning: UV-C light can damage eyes and skin. Always wear appropriate eye, facial, and other PPE during experimentation.

Challenge aerosols were generated using either 100 nm polystyrene latex spheres (Nanospheres, Duke Scientific, Palo Alto, CA) or a broader distribution of silica particles (see SI for details). The challenge aerosol covers the size range used in National Institute for Occupational Safety and Health (NIOSH) test methods (75±20 nm NaCl particles for N95 type masks[19] and dioctylphthalate (185±20 nm) particles for P99 masks[20]) and are similar to the reported individual virus particle diameters of 60 to 140 nm.[21] Material capture efficiency tests were performed on mask coupons using a scanning mobility particle sizer SMPS (TSI 3938NL52, USA), and efficiency calculations were based on number concentrations.

Details are provided in SI for pressure drop testing and material characterization (Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), optical microscopy, and surface contact angle measurements) and structural tensile testing (Figure SI.3).

Results and Discussion

Removal of Aerosolized Particles by UV-treated Masks

Figure 2A shows representative data for filter capture efficiency using a broad distribution of silica particles for masks with and without UV treatment (Figures SI.4-5 show distributions for other masks). Particles are well-captured by the mask materials, with only a slight (1-2%) decrease in capture efficiency towards the smaller (< 100 nm) particles. The average capture efficiency for the N95 masks over the test range (50 to 200 nm) was well above 95%, while the efficiency was lower (~82% on average) for the surgical mask; Figure SI.6 shows the filtration efficiency for each measured size range. UV-C doses of 1 or 10 J/cm^2 did not change ($p<0.05$) this removal efficiency for any of the masks. Likewise, for an equivalent UV-C dose there was no difference in particle removal efficiency between irradiation with 254 nm (lamp) or 265 nm (LED) light. Separate experiments were performed using a second, more narrowly distributed challenge aerosol composed of different particles (polystyrene latex spheres), and the UV treatment also had no effect on particle removal efficiencies (Figure SI.6-7). Collectively, these observations demonstrate that the applied UV treatments do not significantly reduce the particle capture efficiency of the N95 masks , and the masks would likely pass an official NIOSH test.

UV-C Irradiation has Negligible Impact on Material and Physical Properties of Masks

N95 masks are made of multiple layers of polymeric materials. Figure 3 shows optical microscope, SEM, and FTIR data for each layer in Mask A. Based on FTIR vibrational wavelengths,[22, 23] layers 1 and 3 were primarily polypropylene, while layer 2 was polyester. To enhance facial fitting an aluminum nose clip coated with polyurethane foam is used. Elastic straps are composed of braided polyisoprene. Layer 1 differs morphologically from the other layers in mask A (Figure 3A). Layer 1 has a checkerboard configuration of bundled smaller fibers. Similar to layer 1 in Mask A, an inner polymer layer Mask B also exhibited a checkerboard configuration of bundled smaller fibers. Otherwise the polymer fibers were uniform and contiguous (Figure SI.8). Mask B contained multiple polypropylene layers and an additional hard-plastic mesh on its outer layer, intended to resist collapsing. The surgical mask contained 3 layers, two outer cellulose acetate layers and an inner polypropylene layer, which the vendor claims important for aerosol removal.

As illustrated in Figures 3 and SI.9, there was no decrease in FTIR peaks or formation of new peaks after irradiation at 1 or 10 J/cm^2 of UV-C. This is not surprising because photooxidation can only occur when the polymer contains chromophores (e.g., aromatic, C=O, and N=N), which absorb short wavelengths. Even though FTIR showed layer 2 of N95 Mask A contained chromophores (aromatic and C=O vibrations), it could be protected from UV irradiation by layer 1 and 3 of Mask B. Optical microscopy and SEM analysis showed no apparent changes in morphology (fiber diameter, distribution, distribution of indentations, etc.) after UV irradiation (Figure SI.8 and SI.10).

Virus removal in N95 PPE is not limited to a “sieve” effect (i.e., particle interception). Other processes such as impaction, electrostatic interactions, or diffusion can also be important or even dominant depending on the particle size and filtering material.[24] The above morphological and surface chemistry measurements suggest negligible changes to the mask materials at the UV doses applied, consistent with the negligible effect on particle removal. Changes in the morphology of the polymer layers could also manifest in changing the pressure drop across mask materials.[7] In all cases, relative to the non-irradiated controls, we observed no significant difference in pressure drop across any of the masks after irradiation up to 10 J/cm^2. Thus, morphological assessment and pressure drop measurements confirmed negligible impacts created by UV-C irradiation.

Virus particles tend to be shaded in droplets or present as wet aerosol particles. The hydrophobicity of polymers present in any mask layer may impact aerosol removal. Therefore, surface contact angle measurements were performed as an indicator of hydrophobicity. The outer layers of Masks A (θ=125.3 ±3.1 to θ=119.3±4.4; n=5) and B (θ=123.5 ±3.1 to θ=124.9 ±1.4; n=5) exhibited surface contact angles greater than 90°, indicating hydrophobic materials. The inner layers of Masks A and B and the surgical mask were hydrophilic and wetted easily (θ < 90°). After 10 J/cm^2 of UV-C irradiation, the surface contact angle measurements were not significantly different ($p<0.05$).

Mechanical strength and deformation testing of the masks and elastics were conducted. Results (summarized in Figure SI.11) showed that 10 J/cm^2 UV irradiation had negligible impact on mechanical properties for N95 and surgical masks. Mask A had a higher strength (110–125 lbf) than Mask B (50–52 lbf), and both were stronger than the surgical mask (18–20 lbf). Mask B had a higher deformation (4–5 in) compared with Mask A (2–3 in) and surgical mask (<0.5 in). Prior work using a bursting strength test with N95 masks similarly concluded that 11 of 13 masks showed no change in strength at a UV-C dose of 120 J/cm^2, but 90% of the masks showed differences between new and UV-C treated masks at very high dosages (950 J/cm^2).[7] Compared with the mask itself, the elastic straps failed at a much lower strength (5–15 lbf). However, there was no effect of UV irradiation of the strength or deformation of elastic straps.

Design considerations for UV-light disinfection reactors to enable reuse of N95 masks

Based upon the a) feasibility to disinfect masks with UV light from literature, b) validation of virus-size aerosol removal by the masks after UV treatment in this study, and c) confirmation that material characteristics, morphology, and strength were unchanged by UV treatment, we concluded reuse of masks following UV treatment should be viable. During our testing it was clear that all surfaces of the N95 mask could be exposed to UV light, albeit perhaps not equal dosages on all surfaces. Because the pleated folds in the surgical mask (Figure 1) resulted in sections of the mask not being directly exposed to UV-C light, UV-C treatment was deemed appropriate for the N95 masks tested but not for masks with pleated folds. The curved surfaces and metal grating (Figure SI.1) impart some reduction in UV dose. We based the delivered UV dose on a spatially averaged series of measurements using a radiometer across multiple locations in the reactor. Future work could use ray-trace modeling in the reactor or use photo-sensitive “paper test-patches” to quantify the minimum UV dosage reaching any surface of N95 masks.

The next step was to design and fabricate a “reactor” suitable to deliver the germicidal UV dose. A “treating room" has been suggested,[25] where large numbers of hanging masks are treated by mobile towers of UV-C lamps. We conducted individual discussions with physicians and first responders who suggested desirable characteristics of a mask treatment system would be: 1) a treatment time of <5 minutes, 2) the ability to treat 5 to 25 masks at a time during shift-changes, and 3) ability to treat and reuse masks multiple times. Ten daily treatment and reuse cycles were considered reasonable, along with weekly disposal of the masks, as other factors (sweat, humidity, etc.) would likely limit additional use of current N95 masks.

Achieving 1 J/cm^2 dose within 5 minutes requires >3 mW/cm^2 of UV-C light to all surfaces of a between 5 to 25 N95 masks. While 265 to 280nm LEDs can disinfect[14] SARS-CoV-2 and they are rapidly improving in output, efficiency, and cost,[26-28] preliminary assessments of reactor designs to meet end-user treatment time and number of masks treated in a reactor deemed LEDs to be less feasible at this time than the lower cost, higher output, and readily-available 254nm low-pressure mercury lamps. A benefit of LED technology could be their ability to be placed in unique, non-linear, geometries that could more effectively provide uniform irradiation of all surfaces on curved masks.[14] Figure SI.12 illustrates a metallic tool storage box "reactor" (30cm *x* 152cm *x* 30cm) equipped with four 120W 254nm lamps with a grated metal rack that supports roughly twenty N95 masks. The mask-treatment prototype reactor includes several safety features and was fabricated in less than 1 week during the pandemic using materials readily available from home-supply stores. Figure SI.12 shows irradiance measurements using a radiometer throughout this reactor, confirming > 9 mW/cm^2 was achieved everywhere. This design enabled delivery of at least 1 J/cm^2 UV-C to both the top and bottom of masks within ~2 minutes. Supplemental information includes designs for the system and safety features and also includes an operational manual.

Assuring the system delivers the intended UV-C dose was, and remains, a challenge. Although it would technically provide additional assurance consistent UV-C dose was delivered, the cost to purchase and install sensor electronics was nearly equivalent to the entire UV-C reactor cost, and thus precluded installation of a real-time radiometer. A lower cost option was to include a timer and thermometer attached to the reactor surface, which heats by 4 to 8 °C when all four lamps are operating properly. The temperature measurements serve as an assessment of system performance. Additionally, we recently procured color-change paper test strips for germicidal light (Intellego Technologies) and validated them against radiometer based measurements for 50 to 200 mJ/cm^2 using irradiation times of 1 to 20 seconds, using the reactor shown in Figure SI.1b. To our knowledge there have been few studies on the validation of UV-C paper "test-strips" that could meet this need, but these appear limited to UV-C dosages < 200 mJ/cm^2.[29] A research need is a low-cost strategy to measure surface UV-C dosage.

Reusing facial masks will help reduce biomedical waste tonnage. Future research should fill critical technical gaps and conduct both techno-economic (TEA) and life cycle analysis (LCA) to understand the extent to which treating and reusing facial masks is beneficial and sustainable in normal healthcare operations (i.e., non-shortage situations). With a functional unit of a facial mask, one critical factor includes the energy associated to deliver a disinfecting UV-C dose and the number of times a mask can be reused.[18] There remains considerable uncertainty in the required UV-C dosage, ranging from 1–10 J/cm^2 to achieve >99.9% reduction in recoverable virus using N95 masks to < 50 mJ/cm^2 for similar inactivation reported for other surfaces.[13, 14, 30] Research is needed to quantify surface effects and determine if higher UV-C dosages penetrate the polymer layers used in the N95 masks. Some papers suggest UV-C exposures exceeding 950 J/cm^2 impart little change in N95 mask pressure drops[7] and thus could be an upper limit on the cumulative life-time of exposures before masks need to be disposed. Studying effects of multiple, sequential UV-C treatments is needed for LCA to be conducted. Robust LCAs would likewise contrast UV-C treatment against other disinfection modalities (e.g., heat, aerosolized H_2O_2, ClO_2). As an alternative to masks designed *a priori* for single-use, numerous creative designs emerging during the pandemic suggest that N95 masks could be redesigned for intentional treatment and reuse. LCAs on strategies to decrease biomedical waste would lessen the environmental impacts of PPE.

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Supporting Information

Supplementary methods, experimental reactor designs and light flux measurements, tensile strength testing, filtration efficiency data, SEM images, FTIR spectra and data interpretation, Figures S1-12, and UV-Disinfection system operation manual.

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Figure 1. Photographs of the three masks studied in this research.

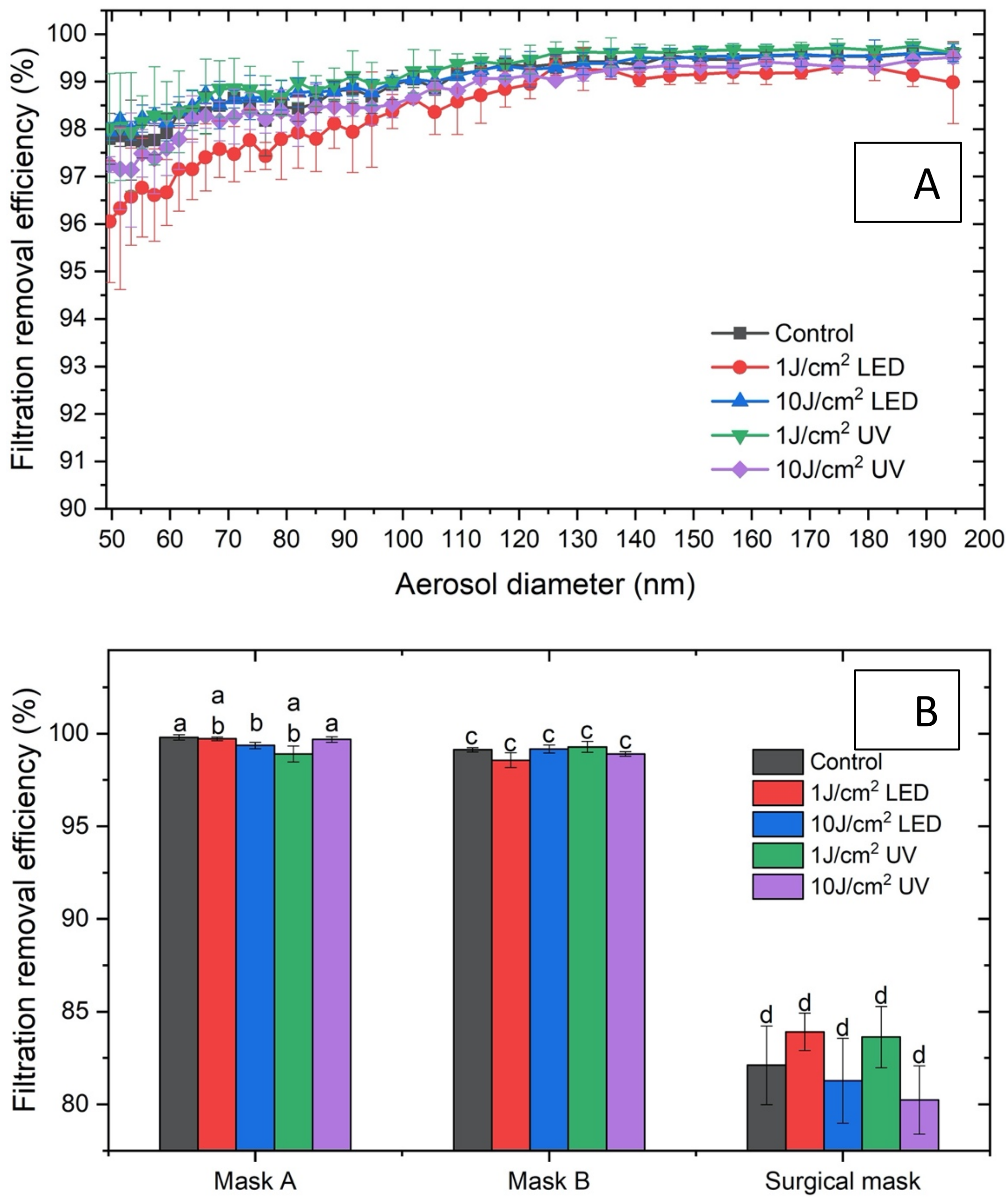

Figure 2. Filtration efficiency comparisons using aerosolized silica particles for three facial masks without UV treatment or with 1 and 10J/cm^2 UV dose delivered by 265nm LED or 254nm mercury lamps. A) shows data for particle removal efficiency between 5 and 220 nm for Mask B. B) shows particle removal efficiencies for all particles between 5 and 220 nm. Error bars show one standard deviation in each direction from the average. Different letters (a, b, c, d) above each bar identify experiments that are statistically different ($p>0.05$) based upon a two-tail paired Student's t-test.

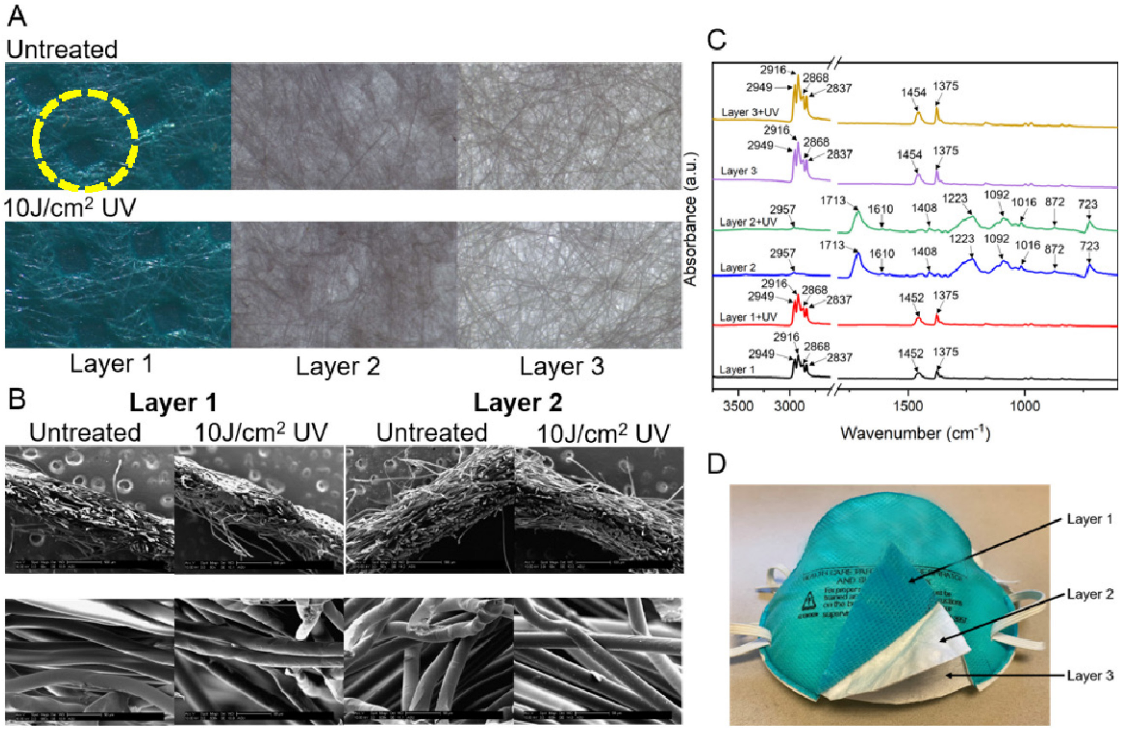

Figure 3. Material characterization for different layers in Mask A using A) optical microscopy where the yellow dashed circle shows a checkerboard pattern of bundled fibers, B) SEM, and C) FTIR, and D) photograph of Mask A showing three polymer layers that were separately characterized.