sustainability

MDPI

Review

Decontamination Methods of N95 Respirators Contaminated with SARS-CoV-2

Thirumaaran Gopalan [1], Rabi'atul 'Adawiyah Mohd Yatim [1], Mohd Ridha Muhamad [1,2,*], Nor Shafina Mohamed Nazari [3], N. Awanis Hashim [4], Jacob John [3] and Victor Chee Wai Hoe [5]

1 Department of Mechanical Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia; thirumaarangopalan@gmail.com (T.G.); rabiatuladawiyahmohdyatim@gmail.com (R.'A.M.Y.)
2 Centre of Advanced Manufacturing and Material Processing (AMMP Centre), Universiti Malaya, Kuala Lumpur 50603, Malaysia
3 Department of Restorative Dentistry, Faculty of Dentistry, Universiti Malaya, Kuala Lumpur 50603, Malaysia; shafina.mnazari@um.edu.my (N.S.M.N.); drjacob@um.edu.my (J.J.)
4 Department of Chemical Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur 50603, Malaysia; awanis@um.edu.my
5 Centre for Epidemiology and Evidence-Based Practice, Department of Social and Preventive Medicine, Faculty of Medicine, Universiti Malaya, Kuala Lumpur 50603, Malaysia; victor@ummc.edu.my
* Correspondence: ridha@um.edu.my; Tel.: +60-3-7967-6806

Abstract: In the preparation and response to the COVID-19 pandemic, a sufficient supply of personal protective equipment (PPE), particularly the face mask, is essential. Shortage of PPE due to growing demand leaves health workers at significant risk as they fight this pandemic on the frontline. As a mitigation measure to overcome potential mask shortages, these masks could be decontaminated and prepared for reuse. This review explored past scientific research on various methods of decontamination of the N95-type respirators and their efficiency against the SARS-CoV-2 virus. Ultraviolet germicidal irradiation (UVGI) and hydrogen peroxide vapor (HPV) show great potential as an effective decontamination system. In addition, UVGI and HPV exhibit excellent effectiveness against the SARS-CoV-2 virus on the N95 respirator surfaces.

Keywords: decontamination; N95 respirators; SARS-CoV-2; COVID-19; ultraviolet germicidal irradiation (UVGI); hydrogen peroxide vapor (HPV); heat; microwave-generated steam (MGS); ethanol

Citation: Gopalan, T.; Mohd Yatim, R.'A.; Muhamad, M.R.; Mohamed Nazari, N.S.; Awanis Hashim, N.; John, J.; Wai Hoe, V.C. Decontamination Methods of N95 Respirators Contaminated with SARS-CoV-2. *Sustainability* **2021**, *13*, 12474. https://doi.org/10.3390/su132212474

Academic Editors: Amir Khorram-Manesh and Krzysztof Goniewicz

Received: 13 September 2021
Accepted: 8 November 2021
Published: 11 November 2021

1. Introduction

According to the WHO, COVID-19 human cases, which are caused by a novel coronavirus named SARS-CoV-2, were first reported in Wuhan City, China, in December 2019 [1]. Due to this unprecedented pandemic, the demand for face mask respirators has surged significantly. The WHO predicted that mask manufacturing industries need to increase manufacturing by 40 percent to meet the demand [2]. Frontline workers rely solely on PPE, especially N95 respirators, to protect themselves from being infected and infecting others. The N95 respirators should be disposed of after a sole patient visit, according to the Centers for Disease Control and Prevention.

Nevertheless, under acute PPE scarcity, it advises prolonged use of N95 respirators (using the same N95 respirator for many patient interactions) with limited reuse (keeping an N95 respirator during interactions for usage across several patients' visits). During the COVID-19 pandemic, due to a shortage of N95 masks, several emergency services have implemented various N95 prolonged use strategies. However, there is insufficient scientific proof that they were successful. In one investigation, researchers examined how often duckbill N95s and dome-shaped N95s masks failed by using fit-tests when they were reused. They concluded that healthcare systems must closely monitor N95 fit throughout extended usage or reuse and avoid using duckbill masks if better options are available [3].

Among the available models of face masks, N95 respirators are designed and intended for healthcare usage [4].

Developing countries whose populations are mostly made up of people living in poverty, such as India, Pakistan, and Sri Lanka, face even greater challenges due to a shortage of masks. The slowed economies in these countries, coupled with a face mask price hike, made people prioritize daily necessities over face masks, promoting the risk of the COVID-19 pandemic still existing in the community [5]. Due to these shortages, health workers were forced to ration their face mask supply to one N95 mask per week with an additional surgical mask on top. In addition, healthcare facilities are restricted to performing some non-COVID-related medical care as these supply limitations are concentrated on COVID-related patients [6].

As a solution, extending the usage of N95 respirators can assist in overcoming the shortage of masks experienced worldwide. Decontamination procedures of face masks that reduce the pathogen burden show great potential to alleviate the shortage of mask issues. According to NIOSH, ultraviolet germicidal irradiation, vaporous hydrogen peroxide, and moist heat have shown the most potential procedures to decontaminate filtering facepiece respirators (FFR) [7].

In essence, the mask shortage problem during the pandemic needs to be addressed immediately. This review aimed to compare the decontamination procedures of the virus on the N95 respirator, particularly highlighting effective but economical methods.

2. Methods

Relevant studies were searched using the PubMed and Preprint platform (medRxiv) electronic databases using a combination of specified MeSH terms that were restricted from 2000 to 2021 (Table 1). Apart from the database searches, several studies were included based on the relevance to this review. In addition, regulatory documents related to the decontamination of N95 respirators were obtained from the official websites of the CDC, the FDA, the WHO, and 3M. Studies were selected for evaluation based on specified inclusion criteria: (a) studies reporting at least one of the selected N95 respirator decontamination procedures for this review (UVGI or HPV or heat or MGS or ethanol); (b) studies reporting at least one of the selected N95 respirator decontamination outcomes (reduction in pathogen load or mask performance or structural integrity of the mask).

Table 1. Studies search strategies and outcomes.

Database	Search Terms	Results (n)	Studies Included (n)
PubMed	((“N95 Respirators”[Mesh]) OR (“Respiratory Protective Devices”[Mesh]) OR (“Personal Protective Equipment”[Mesh])) AND ((“Decontamination”[Mesh]) OR (“Microbial Viability”[Mesh]) OR (“Virus Inactivation”[Mesh]) OR (“Equipment Reuse”[Mesh]) OR (“Sterilization”[Mesh]))	781	35
medRxiv	((N95 respirators) OR (respiratory protective devices)) AND ((decontamination) OR (microbial viability) OR (virus inactivation))	149	12
Other Relevant Studies	Low-cost mask decontamination, N95 decontamination, and SARS-CoV-2 inactivation	-	14

3. SARS-CoV-2

The WHO named the pathogen that causes coronavirus disease (COVID-19) SARS-CoV-2 on 12 February 2020. CoVs is a single-stranded positive-sense RNA (+ssRNA) virus [8]. The schematic structure of the SARS-CoV-2 virus is illustrated in Figure 1. The SARS-CoV-2 virus was reported to possess 80% similarity in the aspect of the genome to previous human coronaviruses. Bats were deduced as the vital host and transmitting medium of the SARS-CoV-2 virus [9]. It was concluded that SARS-CoV-2 is transmitted mainly via respiratory droplets and direct contact [10]. Evaluation of the stability of SARS-CoV-2 on different environmental conditions demonstrated that after seven days, a detectable level of the virus still presents on the outer layer of the surgical mask [11]. The FDA calls for a policy where at least three log reductions must be achieved to sterilize devices intended for skin contact [12].

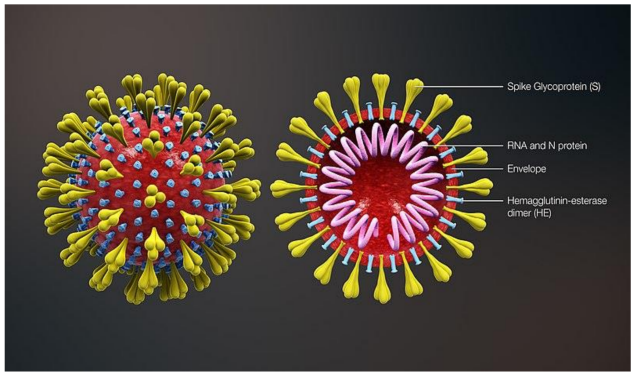

Figure 1. Schematic structure of SARS-CoV-2 [13].

4. The N95 Respirator

The N95 respirator is a type of respiratory protective equipment with a specific design to tightly fit its user. This type of respirator undergoes a testing and evaluation process by NIOSH [14]. In comparison to other FFRs, the N95 respirator offers a minimum of 95% filtration efficiency against particulate aerosols [15]. Quantitative fit testing of FFRs proves the superior protection that the N95 respirator offers [16].

The N95 respirator is made up of four layers, namely, a coverweb, a shell, filter 1, and filter 2 as illustrated in Figure 2. The coverweb and the shell layers are made up of polyester; meanwhile, filter layers are made from polypropylene [4]. The filtration efficiency of the respirator is determined by the internal filtration layer, which is a high-efficiency melt-blown non-woven material [17].

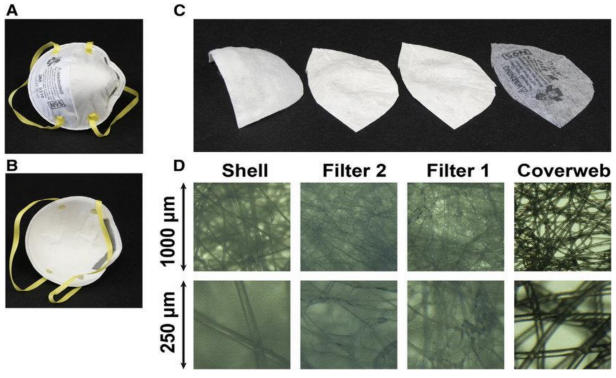

Figure 2. Multilayer sandwich anatomy of N95 mask. (**A**) Environmental interface; (**B**) user interface; (**C**) from left to right: inner layer (shell), middle layers (filter 2 and filter 1), and outer layer (coverweb); (**D**) light microscope images of the four layers, with a lower row at four-fold higher magnification (3M model 8210). Adapted from [18] with permission.

5. Decontamination Treatment for N95 Respirators

5.1. Ultraviolet Germicidal Irradiation (UVGI)

UVGI is a scientifically proven decontamination method that can destroy the protein coating of the SARS-coronavirus, which possesses similar characteristics as the SARS-CoV-2 virus (COVID-19 virus) [19]. Ozog et al. [20] reported excellent decontamination results of the SARS-CoV-2 virus with a 1.5 J/cm^2 UV dose, which was achieved using a 4 UVC lamp set-up. Vo et al. [21] produced the required decontamination levels up to a three-log reduction with a UV dose of 4.32 J/cm^2 and complete decontamination with a $\geq$7.20 J/cm^2 dosage against the MS2 virus. A relatively longer decontamination time was reported due to the low range of UV irradiation used in the research.

Lindsley et al. [22] tested a UV dose up to 950 J/cm^2 on N95 respirators, which resulted in acceptable degradation on filtration performance and no effect in flow resistance. This study reported a perfect range for UVC-based decontamination treatment cycles. Ozog et al. [23] reported excellent fit testing results using N95 respirators with a total exposure of 60 J/cm^2.

5.2. Hydrogen Peroxide Vapor (HPV)

HPV-based decontamination systems are regarded as some of the best decontamination systems due to their efficacy against various microorganisms and their rapid processing cycles [24]. Saini et al. [25] tested the N95 respirator's decontamination against three biological indicators: Escherichia coli, Mycobacterium smegmatis, and spores of Bacillus stearothermophilus using an HPV machine. Excellent decontamination results were reported where decontamination up to a seven-log reduction was achieved using 11–12% HPV against E.coli. Jatta et al. [26] performed decontamination with a 59% HPV concentration using a VPRO maX low-temperature sterilization system. These research results exhibited no significant effect on the filtration performance and fit of the N95 mask after exposure to 59% HPV up to 10 cycles. The range of treatment time reported in this study provides a solid foundation for an HPV-based decontamination system design.

5.3. Heat

5.3.1. Moist Heat

Lore et al. [27] tested moist heat decontamination against the influenza virus applied on an N95 mask. In this study, a contaminated mask was heated to 65 + 5 °C for 3 h. The results show that the required decontamination level (>four-log reduction) was achieved. However, a relatively slow decontamination time can prove to be an inefficient decontamination procedure for everyday application. Rockey et al. [28] investigated the effect of humidity in virus heat inactivation against two bacteriophages (MS2 and phi6), a mouse coronavirus (murine hepatitis virus), and a recombinant human influenza A virus subtype H3N2 (IAV) using a humidity-controlled oven. Heat treatments illustrated greater decontamination results with increasing humidity, where six-log reductions were reported in humidity exceeding 50%.

Bopp et al. [29] tested multiple cycles of autoclaves on N95 respirators. Four different autoclave cycles (115 °C for one hour, 121.1 °C for 30 min, 130 °C for two minutes, and 130 °C for four minutes) were administered to N95 FFRs. N95 FFRs showed negligible differences in their functionality and integrity even after three cycles. Andregg et al. [30] applied heating decontamination to N95 respirators with moisture (85 °C, 60–85% humidity) in a polypropylene container and a convection oven setup. Post-decontamination N95 FFRs exhibited excellent results in both quantitative fit testing and filtration efficiency.

5.3.2. Dry Heat

Xiang et al. [31] implemented dry heat pasteurization for one hour at 70 °C for the N95 respirator's decontamination. This study showed that this procedure can kill six species of respiratory bacteria and one fungi species and can inactivate the H1N1 indicator virus. In addition, neither the performance nor the integrity of N95 respirators showed

significant degradation. This study shows that dry heat is capable of deactivating various pathogens but at a relatively slow rate. Pascoe et al. [32] successfully decontaminated pathogen (*S. aureus*) under dry heat of 70 °C by reducing log 4 in 90 min using a laboratory incubator. Despite strong decontamination results, the slow decontamination rate might prove to be the drawback of this method. Viscusi et al. [33] reported a slight increase in average penetration at N95 respirators when exposed to 80 °C after 60 min. These results can potentially act as a limitation for dry heat exposure to an N95 mask.

5.4. Microwave Generated Steam (MGS)

Fischer et al. [34] have proved up to a four-log reduction in bacteriophage MS2 pathogenic virus using sealed steam bags on a 1100-W-rated microwave for 90 s. In addition, tested N95 respirators also passed the minimum required filtration efficiency requirements of 95%. Zulauf et al. [35] reported a reduction greater than four logs measured in PFU on the N95 respirator. They tested MS2-phage-contaminated N95 respirators to microwave-generated steam for 3 min. Moreover, the respirators exhibited the required filtration performance and integrity even after 20 cycles of 3 min.

5.5. Ethanol

By using ethanol, decontamination of pathogens happens by protein denaturation. At a concentration of 60%–80%, ethanol proves to be effective against lipophilic viruses and many hydrophilic viruses [36]. Liao et al. [37] tested N95 respirators using a 75% ethanol treatment, which was immersed and dried. The filtration efficiency of the N95 respirators were affected considerably with treatment, which indicates that ethanol treatment could not retain the mask's reusability properties.

5.6. Other Methods

N95 respirator decontamination procedures other than the methods selected for this review (UVGI or HPV or heat or MGS or ethanol) are highlighted based on their potential as a low-cost and accessible method. Lendvay et al. [38] tested SARS-CoV-2-inoculated N95 masks under methylene blue (MB) photochemical action for decontamination. They showed that MB activated by red or white light significantly inactivates SARS-CoV-2 on N95 mask surfaces without compromising the specimen's integrity. Excellent virucidal activity of 99.8%–>99% was reported, and preservation of mask integrity proved up to five treatment cycles. Their findings suggested a strategy for decontaminating PPE and masks for reuse that is accessible and inexpensive and that can be used in high-resource and low-resource situations amid supply disruptions. This is due to the worldwide availability of MB light at an affordable cost without using specialized instruments. In addition, the New York City Department of Health and Mental Hygiene has released passive decontamination guidance to health workers to use a paper bag or other clean, breathable containers to store used N95 respirators to prolong their efficiency over multiple usages. The method is as follows. Each day, the healthcare workers would use one N95 respirator with a tagged name and the number of the day used and would place it in a paper bag or a ventilated container at the end of the shift. The mask should be disposed of after the seventh day of use. Healthcare workers must be aware that the N95 respirator could be contaminated albeit at a substantially lower rate. Limited storage periods may be considered, although they may raise the chance of contamination. As the more rigorous disinfecting techniques become accessible, this strategy could be integrated for higher efficiency [39]. Heimbuch et al. [40] evaluated the ability of wipe products available commercially to clean filtering facepiece respirators (FFRs) contaminated with pathogenic or non-pathogenic aerosols. They examined the decontamination effect of benzalkonium chloride, hypochlorite, and nonantimicrobial wipes on the N95 FFRs. The highest particle penetration capacity was observed in benzalkonium chloride wipes. They reported effective decontamination results of S aureus up to 99.72% (exterior of N95) and 98.60% (interior of N95) using benzalkonium chloride (BAC) wipes. Decontamination using wipes is readily

available for public usage, but penetration of respirator due to wipe decontamination must be approached with caution.

5.7. Comparison of Decontamination Treatments for N95 Respirators

The reusability of a disinfected N95 respirator depends on several factors such as inactivation of the targeted organism, the safety of the user, and consistent filtration function and fit of the respirator. UVGI and HPV have demonstrated excellent results as an efficient decontamination method with effective elimination of SARS-CoV-2 virus while preserving the performance of the respirator. However, extensive studies are needed to incorporate HPV- and UVGI-based decontamination systems into a household-based portable commercial-ready product for commercial use. On the other hand, the MGS-based decontamination method exhibits great potential with rapid disinfection for household applications. Currently, there are still few studies about this method for decontamination application. Its rapid method enables a huge potential of applications. However, use in materials that are sensitive to steam could be a concern for material degradation. The other method includes the heat-based decontamination method, which has a major drawback for its time-consuming process and filtration performance degradation in extensive dosages. The conventional method of using ethanol has shown unavoidable degradation of the respirator by using this procedure. Table 2 demonstrates the effects of using a specified N95 decontamination treatment.

Table 2. Advantages and disadvantages of decontamination treatments for N95 respirators.

Decontamination Treatment	Advantages	Disadvantages
Ultraviolet germicidal irradiation (UVGI)	- Proven efficiency against SARS-CoV-2 - Fast disinfection - Easy parameter control (dosage) - No residue	- Not readily available - Basic expertise in handling needed - Mask performance affected at high doses
Hydrogen peroxide vapor (HPV)	- Proven efficiency against SARS-CoV-2 - Excellent virucidal activity against a variety of viruses. - Integrity of mask preserved - Multiple mask decontamination in one cycle	- Not readily available - Expensive - Basic expertise in handling needed - Complete cycle includes multiple stages of decontamination - Require enclosed air circulation set up
Moist heat	- Readily available - Good virucidal activity - No residue - Better decontamination results compared to dry heat decontamination	- Slow disinfection - Integrity of mask affected at high temperatures
Dry heat	- Readily available - Good virucidal activity - No residue	- Slow disinfection - Integrity of mask affected at high temperatures
Microwave-generated steam (MGS)	- Readily available - Good germicidal activity - No residue - Rapid disinfection	- Limited to one mask decontamination per cycle
Ethanol	- No residue	- Not readily available - Significant degradation to respirator integrity and performance

6. Decontamination System Design for N95 Respirators

6.1. Ultraviolet Germicidal Irradiation

Several factors must be taken into account when designing a UVGI-based decontamination system, namely, the wavelength of the ultraviolet rays, the irradiance, and the exposure time. The effectiveness of a UVGI-based decontamination system depends on the dosage of UVC administered to the N95 mask. A safe dosage range must be estimated beforehand because excessive dosage can affect the integrity of the mask. On the other hand, an insufficient dosage can lead to incomplete deactivation of the virus. The UV dose for a specific system can be calculated using Equation (1) [41]. The system specifications and outcomes of studies related to UVGI-based N95 decontamination are listed in Table 3.

$$\text{UV dose}\left(\frac{\text{J}}{\text{cm}^2}\right) = \text{Irradiance}\left(\frac{\text{W}}{\text{cm}^2}\right) \times \text{Time (s)} \quad (1)$$

Table 3. UVGI-based decontamination system specifications and outcomes.

Study	Wavelength (nm)	Irradiance (W/m^2)	Exposure Time (s)	Dosage (J/cm^2)	Distance (cm)	Outcomes
Reduction in Pathogen Load (Various Pathogens)						
[20]	254	165	60–70	3	11.5	- Log reduction of >3 in viable SARS-CoV-2 virus - Mask model: 3M 1860
[42]	253.7	NA	0–300	NA	100	- Log reduction of >4.79 in viable SARS-CoV-2 virus - Mask model: 3M 1860
[43]	254	54.3	2–420	0.01086–2.2806	10	- Log reduction of up to 3.5 in viable SARS-CoV-2 virus - Mask model: 3M 8211
[44]	254	10	300 600	0.3 0.6	NA	- Average log reduction of 3.74 in viable SARS-CoV-2 virus at 0.6 J/cm^2 dosage (3M 1860) - Average log reduction of 1.68 in viable SARS-CoV-2 virus at 0.6 J/cm^2 dosage (3M 8210) - Mask model: 3M 1860 and 3M 8210
[45]	254	3.18	1980	0.63	NA	- No significant log reduction in viable SARS-CoV-2 RNA - Mask model: 3M 1860
[46]	260–285	5.5	600–3600	0.33–1.98	50	- Log reduction of ≥3 in viable SARS-CoV-2 virus - Mask model: AOSafety N9504C
[47]	254	64	NA	0.05–1.5	3.4	- Log reduction of >3 in viable SARS-CoV-2 virus at 0.05–0.5 J/cm^2 dosage - Log reduction of >5 in viable SARS-CoV-2 virus at 0.5–1.5 J/cm^2 dosage - Mask model: 3M 1860
[48]	254	2.32	0–3600	0–0.8352	60.96	- Log reduction of >3 (5 min of exposure) and complete decontamination (15 min of exposure) in viable NL63 coronavirus - Mask model: 3M 1860
[49]	NA	NA	120	2.6	NA	- No virus detection after 2 or 5 cycles (porcine coronavirus and murine norovirus) - Mask model: KN95 FFR (Guangzhou Sunjoy Auto Supplies)
[41]	254	3900	60	1	100	- Log reduction of 3 in viable H1N1 influenza virus - Mask model: 3M 1860
[27]	254	16–22	900	1.8	25	- Log reduction of ≥4.65 in viable H5N1 influenza virus - Mask model: 3M 1860

Table 3. *Cont.*

Study	Wavelength (nm)	Irradiance (W/m^2)	Exposure Time (s)	Dosage (J/cm^2)	Distance (cm)	Outcomes
[21]	253.7	4	3600–18,000	1.44–7.2	42	- Log reduction of ≥3 in viable MS2 at 4.32 J/cm^2 - No virus detection at ≥7.20 J/cm^2 - Mask model: Honeywell N1105
[50]	254	≥300	60	≥2	NA	- Log reduction of ≥3 in viable MS2 - Mask model: 3M 1860
[51]	254	25	120–15,960	0.0038–0.4707	NA	- Log reduction of >3 in viable MS2 at 0.1 J/cm^2 - Mask model: 3M 1860
[52]	254	NA	300	0.126	NA	- Complete inactivation of *E. coli* and *B. subtilis* after 300 s of exposure - Mask model: UVEX FFP2
			600	0.256		
			900	0.378		
[53]	200–315	0.069–0.1072	300	NA	180	- Log reduction of 0.5–1.3 in MS2 - Log reduction of 0.0–2.0 in phi6 - Log reduction of 0.8–1.7 in IAV - Log reduction of 1.3–1.7 in MHV - Mask model: 3M 1860
[54]	254	189	60–1200	1.134–22.68	10	- UVA could not decontaminate as effectively as UVC - No bacteria recovered after 5 min of UVC exposure - Mask model: 3M 8210
	365	312		1.872–37.44		
Performance or Structural Integrity						
[22]	254	NA	NA	0–950	6.2	- Filtration performance slightly affected - No effect on flow resistance - Mask model: 3M 1860
[27]	254	16–22	900	1.8	25	- Mean penetration: 0.99% at 300nm - Mask model: 3M 1860s
[37]	254	NA	1800	NA	NA	- Efficiency of meltblown layer: (≥96% at 10 cycles) and (≥93% at 20 cycles) - Mask model: 3M 8210
[45]	254	3.18	57,600 (Exterior)	18.4	NA	- Mask integrity was significantly impaired - Average fit score: ≥ 100 - Mask model: 3M 1860
			14,400 (Interior)	4.6		
[49]	NA	NA	120	2.6	NA	- Remained physically unaffected up to 5 cycles - Filtration efficiency of >95% up to 5 cycles - Breathability well within allowed range after 5 cycles - Mask model: KN95 FFR (Guangzhou Sunjoy Auto Supplies)
[52]	254	NA	300	0.126	NA	- Filtration efficiency maintained up to dosage of 0.378 J/cm^2 - Mask model: UVEX FFP2
			600	0.256		
			900	0.378		
[55]	254	≥24.31	NA	≥1	30.48	- Expected penetration: 1.121% (0.3µm, 5 cycles, 3M 1860) and 0.258% (0.3µm, 5 cycles, 3M 8210) - Mask model: 3M 1860 and 3M 8210
[56]	NA	NA	300	>1	100	- Filtration performance preserved up to 10 cycles - Mask model: 3M 8210
[57]	254	55.56	180	1	36.8	- No visual abnormalities on mask integrity - Mean breaking force of 34.8 ± 5.23 N - Average filtration efficiency = >95% - Fit factor = >100% - Mask model: 3M 8110S

6.2. Hydrogen Peroxide Vapor (HPV)

Most of the studies reviewed here used commercially available HPV-based decontamination machines. The efficiency of HPV-based decontamination systems depends on the concentration of the HPV used coupled with the time of exposure to the N95 respirator.

HPV traces on mask surfaces might induce health hazards. Therefore, each HPV-based decontamination system must be able to produce residue-free N95 respirators upon the decontamination cycle. The system specifications and outcomes of studies related to HPV-based N95 decontamination are listed in Table 4.

Table 4. HPV-based decontamination system specifications and outcomes.

Study	Method	Concentration of HPV Used/Achieved	Exposure Time (min)	Outcome
Reduction in Pathogen Load (Various Pathogens)				
[45]	Bioquell Z vaporizer	30% (Peak 500 ppm)	Gassing: 20 Dwell: 60 Aeration: 210	- Log reduction of ≈5 in viable SARS-CoV-2 RNA - Mask model: 3M 1860
[46]	Panasonic MCO-19AIC-PT	≈ 1000 ppm	Gas: 7	- Log reduction of ≥ 3 viable SARS-CoV-2 virus - Mask model: AOSafety N9504C
[58]	VHP® ARD system	35% (Peak 750 ppm)	Conditioning: 3 Decontamination: 30 Aeration: 20	- Log reduction of 5.2–6.3 in viable SARS-CoV-2 virus - Mask model: 3M 1860 and 3M 8210
[59]	V-PRO maX low-temperature sterilization system by Steris	NA	Non-lumen cycle: 28	- Log reduction of 4 in viable SARS-CoV-2 titer and 5 in HCoV-229E - Mask model: 3M 8210
[60]	Steris ARD1000®	410 ± 83 ppm	Gas: 180	- Log reduction of >4 in viable SARS-CoV-2 - Mask model: 3M 1860
[49]	V-PRO maX low-temperature sterilization system by Steris	59%	Non-lumen cycle: 28	- No virus detection after 2 or 5 cycles (porcine coronavirus and murine norovirus) - Mask model: KN95 FFR (Guangzhou Sunjoy Auto Supplies)
[61]	A novel HPV-based system was constructed	3%	Gassing: 3–5 Dwell: 60 Aeration: 15	- Log reduction of >6 in P22 bacteriophage - Mask model: 3M 1860
[62]	Bioquell® BQ-50	35%	NA	- No growth of 6-log Geobacillus stearothermophilus spores post decontamination - Mask model: 3M 1860
[63]	VHP® VICTORY unit	35% (400–800 ppm)	Conditioning and Gassing: 90 Dwell: 180 Aeration: 900–1080	- No growth of 6-log Geobacillus stearothermophilus spores post decontamination (1st, 7th day) - Mask model: 3M 1860s
Performance or Structural Integrity				
[26]	V-PRO maX low-temperature sterilization system by Steris	59%	Inject: 18 Aeration: 8	- Mask fit and filtration efficiency preserved up to 10 cycles - Mask model: 3M 8211
[45]	Bioquell Z vaporizer	30% (Peak 500 ppm)	Gassing: 20 Dwell: 60 Aeration: 210	- Mask integrity minimally affected - Average fit score: ≥ 100 - Mask model: 3M 1860
[46]	Panasonic MCO-19AIC-PT	≈ 1000 ppm	Gas: 7	- Filtration performance preserved after 1 treatment - Mask model: AOSafety N9504C

Table 4. *Cont.*

Study	Method	Concentration of HPV Used/Achieved	Exposure Time (min)	Outcome
[49]	V-PRO maX low-temperature sterilization system by Steris	59%	Non-lumen cycle: 28	- Remained physically unaffected up to 5 cycles - Filtration efficiency of >95% up to 5 cycles - Breathability well within allowed range after 5 cycles -Mask model: KN95 FFR (Guangzhou Sunjoy Auto Supplies)
[55]	V-PRO maX low-temperature ster-ilization system by Steris (Masks were enclosed within Vis-U-AllTM low-temperature sterilization pouches)	59%	Full cycle: 28	- Expected penetration: 0.277% (0.3µm, 5 cycles, 3M 1860) and 0.424% (0.3µm, 5 cycles, 3M 8210) - Mask model: 3M 1860 and 3M 8210
[58]	VHP® ARD system	35% (Peak 750 ppm)	Conditioning: 3 Decontamination: 30 Aeration: 20	- Structural and functional integrity preserved - Mask model: 3M 1860 and 3M 8210
[59]	V-PRO maX low-temperature sterilization system by Steris	NA	Non-lumen cycle: 28	- Filtration efficiency retained - Mask model: 3M 8210
[60]	Steris ARD1000®	410 ± 83 ppm	Gas: 180	- Mask fit and filtration efficiency preserved after 1 cycle - Mask model: 3M 1860
[61]	A novel HPV-based system was constructed	3%	Gassing: 3–5 Dwell: 60 Aeration: 15	- Minimum required filtration efficiency value of 95% preserved up to 20 cycles - Mask model: 3M 1860
[62]	Bioquell® BQ-50	35%	NA	- All processed masks passed fit testing - Mask model: 3M 1860
[64]	V-PRO maX low-temperature sterilization system by Steris	NA	Non-lumen cycle: 28	- Filtration efficiency significantly affected (80.4–91.8%), particularly at a lower particle diameter - Mask model: 3M 8210
[65]	VHP® VICTORY unit	35% (400–800 ppm)	Conditioning and Gassing: NA Dwell: 180 Aeration: overnight	- Integrity (mask fit) of the mask preserved up to 8 decontamination cycles - Mask model: 3M 1860s
[66]	V-PRO maX low-temperature ster-ilization system by Steris (masks were enclosed within Tyvek pouches)	NA	Non-lumen cycle: 28	- 66% of the respirators failed fit testing after one decontamination cycle - Mask model: 3M 1860s
[67]	Bioquell Clarus C	35% (±480 ppm)	Gassing: 25 Dwell: 20	- All the tested masks passed fit testing up to 10 cycles - Mask model: 3M 1870 +

6.3. Heat

Heat treatments can sterilize microbes by altering their membranes and denaturing proteins [68]. Heat-related decontaminations can be divided into two main classifications, namely, moist-heat and dry-heat decontamination. The efficiency of a heat-based decontamination system depends on the working temperature, the presence of humidity, and the exposure time. The existence of moisture in the heating procedure is proven to promote better decontamination results. The system specifications and outcomes of studies related to moist heat and dry heat-based N95 decontamination are listed in Tables 5 and 6 respectively.

Table 5. Moist-heat-based decontamination system specifications and outcomes.

Study	Method	Temperature (°C)	Exposure Time (min)	Relative Humidity (%)	Outcome
Reduction in Pathogen Load (Various Pathogens)					
[69]	- 57 L model BD 56 standard incubator - Humidity induced by placing 400 mL of water-filled pan below the incubator	70	180–360	≈<5–32	- Complete decontamination of SARS-CoV-2 at 5 hrs of exposure - Mask model: 3M 1860, 3M 8210, and Moldex 1510
[70]	- Multicookers with the sous vide function - Humidity induced by placing 500 mL of water in the multicooker pot	65	30	94 ± 0.5 (measured inside the paper bag)	- Inactivation of SARS-CoV-2 virus beyond detection limit within 10 min of exposure - Stacked mask does not hinder decontamination - Mask model: 3M 1860 and 3M 8210
[27]	- Mask loaded to a sealed container placed inside a heated oven - Container filled with 1 L tap water	65 ± 5	20	NA	- Log reduction of ≥4.62 log in viable H5N1 influenza - Mask model: 3M 1860
[71]	- Circulating water bath	60 ± 2	30	80 ± 5	- Log reduction of ≥4.35 in influenza A virus (InfA) - Log reduction of >5.32 in *S. aureus* - Mask model: 3M 1860s
[28]	- Conducted using TestEquity 123H temperature/humidity chamber	72, 82	30	1–89	- Increase in treatment temperature and humidity results in an increased log reduction of pathogen - Mask model: 3M 1860
[52]	- Samples were steamed above boiling water	NA	30, 60, 90	70–85	- Log reduction of >4 in *E. coli* and *B. subtilis* at 30 and 90 min of exposure - Mask model: UVEX FFP2

Table 5. *Cont.*

Study	Method	Temperature (°C)	Exposure Time (min)	Relative Humidity (%)	Outcome
[53]	- Ziploc container	80	30	≈70	- Log reduction of >6.9 in MS2 - Log reduction of >7.2 in phi6 - Log reduction of >3.4 in IAV - Log reduction of >0.4 in MHV - Mask model: 3M 1860
	- Humidity-controlled oven	82	30	≈50	- Log reduction of >6.6 in MS2 - Log reduction of >6.7 in phi6 - Log reduction of >3.9 in IAV - Log reduction of >2.7 in MHV - Mask model: 3M 1860
[72]	- BevLes heated holding cabinet with humidity (masks were enclosed within steril-peel pouches)	70, 90	60	0, 25, 40, 50, 70	- Inactivation of E. coli beyond detection limit at (70 °C, 50%RH) and (90 °C, 70%RH) - Mask model: 3M 1860s
	Performance or Structural Integrity				
[27]	- Mask loaded to a sealed container placed inside a heated oven - Container filled with 1 L tap water	65 ± 5	20	NA	- Mean penetration of 1.04% at 300-nm particle size - Mask model: 3M 1860
[29]	- Moist-heat autoclave	115–130	2–60	NA	- Molded N95 respirators failed all tested fit testing - Slight degradation to filtration efficiency was notable - Mask model: 3M 1860
[30]	- Conducted using a convection oven (Despatch LAC1-38-8, 3.7 cu. Ft.)	70–85	30	60–85	- Passed fit testing - Filtration efficiency not affected - Mask model: 3M 1860
[52]	- Samples were steamed above boiling water	NA	30, 60, 90	70–85	- Slight decrease in filtration efficiency from 98.86% and 99.51% to 97.58% and 98.79% for 50 and 100 nm particles, respectively - Mask model: UVEX FFP2
[55]	- Masks were enclosed in STERIL-PEEL® sterilization pouches and loaded into the convection heating system with controlled humidity.	75	60	75	- Expected penetration: 1.195% (0.3 µm, 5 cycles, 3M 1860) and 1.924% (0.3 µm, 5 cycles, 3M 8210) - Mask model: 3M 1860, 3M 8210, and Moldex 1510
[69]	- 57 L model BD 56 standard incubator - Humidity induced by placing 400 mL of water-filled pan below the incubator	70	180–360	≈<5–32	- Structural and functional integrity of the respirators preserved up to five cycles - Mask model: 3M 1860, 3M 8210 and Moldex 1510

Table 5. *Cont.*

Study	Method	Temperature (°C)	Exposure Time (min)	Relative Humidity (%)	Outcome
[70]	- Multicookers with the sous vide function - Humidity induced by placing 500 mL of water in the multicooker pot	65	30	94 ± 0.5 (measured inside the paper bag)	- Collection efficiency and inhalation resistance was above the required value of >95% and <35 mmH2O, respectively, for all tested masks upon 5 treatment cycles - A slight change (<10%) in strap elasticity was noted for mask model 3M 1860 - Mask model: 3M 1860 and 3M 8210
[72]	- BevLes heated holding cabinet with humidity (masks were enclosed within steril-peel pouches)	70, 90	60	0, 50	- All processed masks passed fit testing up to 15 cycles - Excellent filtration efficiency of >95%. - Breathing resistance was well within the tolerable resistant standard - Mask model: 3M 1860s and 3M 8210
[73]	- Cylindrical chamber tabletop autoclave (Kronus S18)	121	17	NA	- No visible damage to the mask after treatment - Slight degradation to filtration capacity of 94.4 ± 1.6% after three cycles - Number of reuse does not affect the flow resistance of the mask - Mask model: 3M Aura 1862+
[74]	- Steris Amsco 400 Series prevacuum steam sterilizer model 20	121	30	NA	- 100% (1 cycle) and 86% (2 cycles) of the samples passed fit testing - Mask model: AO Safety 1054S Pleats Plus
[75]	NA	121	20	NA	- Decrease of 20 Pa in respiratory resistance after 4 cycles - Mask model: Duckbill FPP2
[76]	- Sealed respirator container placed inside boiled water	>65	30	50	- Filtration efficiency was recorded above 97% up to 5 cycles - Mask model: Kimberly Clark

Table 6. Dry-heat-based decontamination system specifications and outcomes.

Study	Method/Equipment	Temperature (°C)	Exposure Time (min)	Outcome
Reduction in Pathogen Load (Various Pathogens)				
[72]	BevLes heated holding cabinet with humidity (masks were enclosed within steril-peel pouches)	70	60	- Inactivation of SARS-CoV-2 virus beyond the detection limit - Mask model: 3M 1860s and 3M 8210
[77]	Laboratory dry oven (Fisher Scientific Isotemp 500 series)	60–75	30, 60	- N95 coupons placed in tissue culture plate wells yielded better decontamination results compared to the one placed in parchment paper - No required SARS-CoV-2 virus inactivation achieved in suspended intact N95 respirators - Mask model: 3M 1860, 3M 1860s, and 3M 8200
	Open drying (room conditions)	22–23	7200	- 5/9 coupons contained live SARS-CoV-2 virus - Mask model: 3M 1860s
[49]	FFRs hung horizontally on a metal frame were inserted into an electrically heated vessel	102 ± 4	60 ± 15	- No virus detection after 2 or 5 cycles (porcine coronavirus and murine norovirus) - Mask model: KN95 FFR (Guangzhou Sunjoy Auto Supplies)
[31]	Electric oven	60, 70	60–180	- 1 h of exposure could successfully kill 7 types of bacteria as well as inactivate the H1N1 virus - Mask model: 3M 1860
Performance or Structural Integrity				
[31]	Electric oven	60, 70	60–180	- No significant effect on the shape and filtration efficiency after exposure up to 3 h - Mask model: 3M 1860
[49]	FFRs hung horizontally on a metal frame were inserted into an electrically heated vessel	102 ± 4	60 ± 15	- Signs of degradation or burning visible after 5 cycles - Filtration efficiency dropped to 94.16% after 3 cycles - Breathability well within allowed range after 5 cycles - Mask model: KN95 FFR (Guangzhou Sunjoy Auto Supplies)
[55]	VWR® forced air oven	100	30	- Expected penetration: 0.562% (0.3 µm, 5 cycles, 3M 1860) and 8.107% (0.3 µm, 5 cycles, 3M 8210) - Mask model: 3M 1860 and 3M 8210
[78]	5-sided heating vacuum oven	75	30	-No effect on the fit factor of the mask up to 5 cycles - Mask model: 3M 8210
[79]	Oven (masks were enclosed within nylon heat-resistant bags)	65, 86	34–56	- All processed masks passed fit testing - Mask model: 3M 8810, 3M 8833, and 3M 8835

6.4. Microwave-Generated Steam (MGS)

MGS-based decontamination has enormous potential for wide application as it can be done with household items. It offers a rapid disinfection rate with minimal expertise needed to perform this treatment. The efficiency of MGS-based decontamination is affected by exposure time and is specific to the design of the selected face mask model for the treatment. However, many protocols use commercial steam bags or special materials that are available in laboratories. The system specifications and outcomes of studies related to MGS-based N95 decontamination are listed in Table 7.

Table 7. Microwave-generated steam (MGS)-based decontamination system specifications and outcomes.

Study	Method/Equipment	Exposure Time (s)	Outcome
Reduction in Pathogen Load (Various Pathogens), Performance or Structural Integrity			
[34]	- N95 respirators placed inside Medela Quick CleanTM MICRO-STEAMTM BAGS - Steam bags were placed inside Sharp Model R-305KS (2450 MHz, 1100 W) microwave oven	90	- Log reduction of ≥3 in viable MS2 - Filtration efficiency preserved after 1 cycle - Mask model: 3M 1860 and 3M 8210
[35]	- 1150 W and 1100 W microwave oven used - 1st set up: N95 respirator placed on mesh over mug containing water - 2nd set up: N95 respirator placed on mesh over glass container containing water	180	- Log reduction of ≥4 in viable MS2 with one cycle - Fit, seal, and filtration preserved up to 20 cycles - Mask model: 3M 1860
[52]	- Household microwave oven (Wave 300, 400 W) was used - FFR circular samples were placed on a plastic Petri dish	4–6 (Multiple specified cycles)	- Log reduction of >4 in *E. coli* and *B. subtilis* at 10 and 20 min of exposure - Filtration efficiency maintained - Mask model: UVEX FFP2

6.5. Ethanol

Ethanol-based disinfection is used widely around the world as an effective decontamination method. However, ethanol-based treatment does not produce an efficient result in the decontamination of N95 respirators. Ethanol is known to degrade the structure of the mask's filtration and thus affects the integrity and performance of treated N95 respirators. The system specifications and outcomes of studies related to ethanol-based N95 decontamination are listed in Table 8.

Table 8. Ethanol-based decontamination system specifications and outcomes.

Study	Concentration Used	Exposure Time (h)	Outcome
Reduction in Pathogen Load (Various Pathogens)			
[45]	- 70% ethanol was sprayed 10 times on the mask exterior and 5 times on the interior - Placed in a sealed plastic bag overnight	Air drying: ~8	- No detection of viable SARS-CoV-2 RNA - Mask model: 3M 1860
[52]	- Samples were immersed in 75% ethanol for 2 min	Depends on air drying time	- Complete inactivation of *E. coli* and *B. subtilis* - Mask model: UVEX FFP2
Performance or Structural Integrity			
[37]	- Samples were immersed in 75% ethanol	Depends on air drying time	- Significant decrease in filtration efficiency ($56.33 \pm 3.03\%$) - Mask model: 3M 8210
[45]	-70% ethanol was sprayed 10 times on the mask exterior and 5 times on the interior - Placed in a sealed plastic bag overnight	Air drying: ~8	- Mask integrity was significantly impaired - Average fit score: ≥100 - Mask model: 3M 1860
[52]	- Samples were immersed in 75% ethanol for 2 min	Depends on air drying time	- Significant decrease in filtration efficiency - Mask model: UVEX FFP2
[80]	- Approximately 50 mL of 70% ethanol solution was poured over each mask	Air drying: 2–3	- Filtration efficiency of the mask dropped by 20–30% - It was also noted that 99% of their initial filtration efficiency was restored after vacuum drying - Mask model: 3M 8200, 3M 8210, and 3M 8511

7. Effectiveness of Decontamination Systems against SARS-CoV-2

The effectiveness of a specific decontamination system depends on critical parameters such as the exposure time. UVGI and HPV were investigated further in this review on their effectiveness against SARS-CoV-2, specifically from the surfaces of N95 respirators. The relationship between parameter control and effectiveness against the SARS-CoV-2 virus is illustrated in Figures 3 and 4.

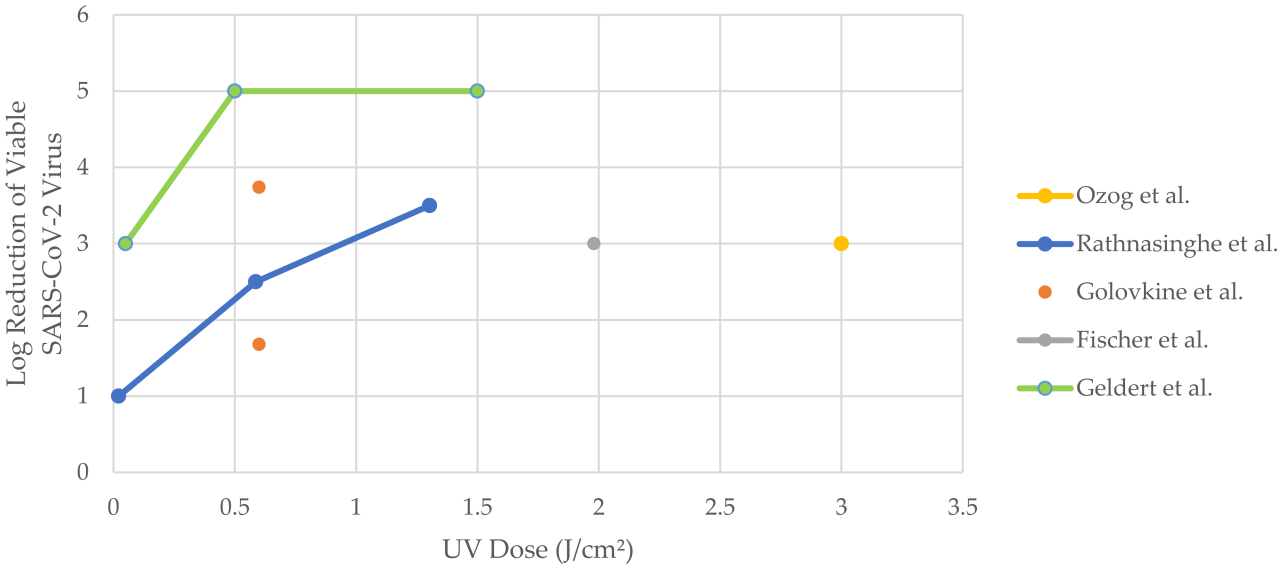

Figure 3. Log reduction of viable SARS-CoV-2 virus with increasing UV dose (data represented in Figure 3 exhibit minimum log reduction achieved by specific dosage as upon reaching the limit of detection (LOD)—real data are not quantifiable).

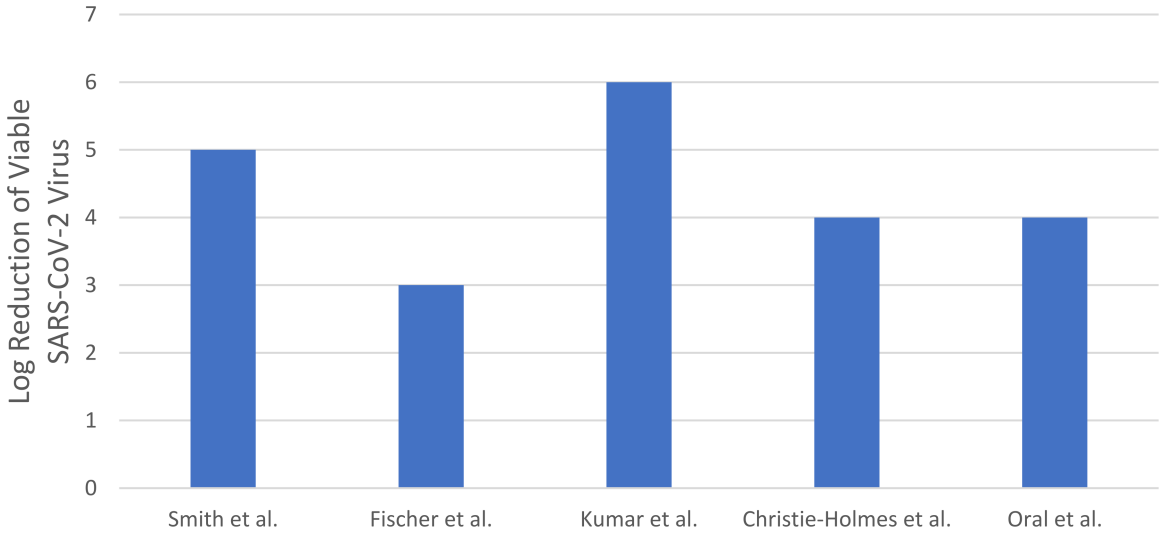

Figure 4. Log reduction of viable SARS-CoV-2 virus with various HPV-based decontamination settings (data represented in Figure 4 exhibit minimum log reduction achieved by specific dosage as upon reaching the limit of detection (LOD)—real data are not quantifiable).

7.1. Ultraviolet Germicidal Irradiation

In a study, Ozog et al. [20] had demonstrated successful decontamination when an N95 mask was irradiated with 1.5 J/cm^2 of UVC (254nm). It was concluded that the dose applied was sufficient. However, a concern on the disinfection of the strap arises due to its coverage by UVC on the strap surface. Rathnasinghe et al. [43] presented a simple UVC decontamination device without the mask's strap decontamination. Golovkine et al. [44],

Smith et al. [45], Fischer et al. [46], and Geldert et al. [47] investigated and compared the efficiency of UVC-based decontamination systems for N95 respirators with other decontamination methods such as ethanol, heat, UVA, ethylene oxide, hydrogen peroxide plasma and vapor, MGS, bleach, and liquid hydrogen peroxide. Comparing across the studies, a UVC-based N95 disinfection treatment with a dosage of greater than 0.5 J/cm^2 can achieve the minimum pathogen load reduction required of three-log reduction against the SARS-CoV-2 virus. As Figure 3 illustrates, Geldert et al. [47] demonstrated notable disinfection of five-log reduction at a relatively low dosage of 0.5 J/cm^2. Nevertheless, the reported sharp decline in the log reduction of SARS-CoV-2 [47] at lower UVC doses (0–0.5 J/cm^2) must be addressed with caution.

7.2. Hydrogen Peroxide Vapor (HPV)

Smith et al. [45], Fischer et al. [46], Kumar et al. [58], Christie-Holmes et al. [59], and Oral et al. [60] have investigated the efficiency of HPV-based decontamination systems for N95 respirators against the SARS-CoV-2 virus. All the studies that reported HPV-based decontamination against the SARS-CoV-2 virus were designed using commercially available HPV generating machines. The comparison of the HPV-based N95 decontamination system efficiency across the studies is presented in Figure 4. The concentration of hydrogen peroxide exposed and the treatment time of a complete cycle comprised of four different processes are the variables that play a significant part in HPV-based decontamination systems to deliver the required decontamination efficiency. Notably, Kumar et al. [58] demonstrated a significant reduction in SARS-CoV-2 of six-log reduction while preserving the functional integrity of the N95 respirator post-treatment.

8. Conclusions

The COVID-19 pandemic shows the severity of the needed supply of PPE for healthcare workers to stay protected at all times. Decontamination of PPE could be an essential measure to mitigate the immediate risk of running out of PPE supply. UVGI- and HPV-based decontamination systems exhibit great potential as a good choice for N95 respirator decontamination. The study indicated that the UVGI and HPV methods could be used to deactivate the SARS-CoV-2 virus without affecting the integrity of the respirator. The excellent virucidal activity of UVGI- and HPV-based decontamination systems suggested that they are good candidates for N95 respirator decontamination.

Author Contributions: Conceptualization, M.R.M., N.S.M.N., N.A.H., J.J., and V.C.W.H.; methodology, M.R.M., T.G., and R.'A.M.Y.; software, R.'A.M.Y.; validation, M.R.M., N.S.M.N., N.A.H., J.J., and V.C.W.H.; formal analysis, T.G.; investigation, T.G.; resources, M.R.M., T.G., and R.'A.M.Y.; data curation, T.G.; writing—original draft preparation, T.G.; writing—review and editing, T.G. and R.'A.M.Y.; visualization, M.R.M. and T.G.; supervision, M.R.M.; project administration, M.R.M.; funding acquisition, M.R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by AUN/SEED-Net, grant number UMSPRAC 2101.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within this article.

Acknowledgments: The authors would like to thank Mohd Fauzi Bakri Hashim for his assistance in this research project.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. World Health Organization. *Coronavirus Disease 2019 (COVID-19): Situation Report*, *94*; World Health Organization: Geneva, Switzerland, 2020.
2. World Health Organization. Shortage of Personal Protective Equipment Endangering Health Workers Worldwide. Available online: https://www.who.int/news/item/03-03-2020-shortage-of-personal-protective-equipment-endangering-health-workers-worldwide (accessed on 16 July 2021).
3. Degesys, N.F.; Wang, R.C.; Kwan, E.; Fahimi, J.; Noble, J.A.; Raven, M.C. Correlation Between N95 Extended Use and Reuse and Fit Failure in an Emergency Department. *JAMA* **2020**, *324*, 94–96. [CrossRef] [PubMed]
4. 3M. 3M™ Particulate Respirator, 8210, N95 Technical Specifications. Available online: https://multimedia.3m.com/mws/media/1425070O/3m-particulate-respirator-8210-n95-technical-specifications.pdf (accessed on 16 July 2021).
5. Gray, A. Exploring the Shortage of Affordable Masks in Developing Countries. Available online: https://www.borgenmagazine.com/affordable-masks/ (accessed on 6 September 2021).
6. Parshley, L. The Mask Shortage Is Forcing Health Workers to Disregard Basic Coronavirus Infection Control. Available online: https://www.vox.com/2020/4/3/21206726/coronavirus-masks-n95-hospitals-health-care-doctors-ppe-shortage (accessed on 6 September 2021).
7. Centers for Disease Control and Prevention. Implementing Filtering Facepiece Respirator (FFR) Reuse, Including Reuse after Decontamination, When There Are Known Shortages of N95 Respirators. Available online: https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html (accessed on 16 July 2021).
8. Chen, Y.; Liu, Q.; Guo, D. Emerging coronaviruses: Genome structure, replication, and pathogenesis. *J. Med. Virol.* **2020**, *92*, 418–423. [CrossRef] [PubMed]
9. Shereen, M.A.; Khan, S.; Kazmi, A.; Bashir, N.; Siddique, R. COVID-19 infection: Emergence, transmission, and characteristics of human coronaviruses. *J. Adv. Res.* **2020**, *24*, 91–98. [CrossRef] [PubMed]
10. Zhang, Y.; Geng, X.; Tan, Y.; Li, Q.; Xu, C.; Xu, J.; Hao, L.; Zeng, Z.; Luo, X.; Liu, F.; et al. New understanding of the damage of SARS-CoV-2 infection outside the respiratory system. *Biomed. Pharmacother.* **2020**, *127*, 110195. [CrossRef]
11. Chin, A.W.H.; Chu, J.T.S.; Perera, M.R.A.; Hui, K.P.Y.; Yen, H.L.; Chan, M.C.W.; Peiris, M.; Poon, L.L.M. Stability of SARS-CoV-2 in different environmental conditions. *Lancet Microbe* **2020**, *1*, e10. [CrossRef]
12. Turtil, S. Sterility Review of 510(k) Submissions: Common Microbiology Issues Found in 510(k) Submissions. Available online: https://www.fda.gov/media/141277/download (accessed on 16 July 2021).
13. Scientific Animations Inc. 3D Medical Animation Corona Virus. Available online: https://commons.wikimedia.org/wiki/File:3D_medical_animation_corona_virus.jpg (accessed on 16 July 2021).
14. Centers for Disease Control and Prevention (CDC); National Institute for Occupational Safety and Health. Understanding the Diffrence. Available online: https://www.cdc.gov/niosh/npptl/pdfs/understanddifferenceinfographic-508.pdf (accessed on 16 July 2021).
15. Ji, D.; Fan, L.; Li, X.; Ramakrishna, S. Addressing the worldwide shortages of face masks. *BMC Mater.* **2020**, *2*, 9. [CrossRef]
16. O'Kelly, E.; Arora, A.; Pirog, S.; Ward, J.; Clarkson, P.J. Comparing the fit of N95, KN95, surgical, and cloth face masks and assessing the accuracy of fit checking. *PLoS ONE* **2021**, *16*, e0245688. [CrossRef]
17. Henneberry, B. How to Make N95 Masks. Available online: https://www.thomasnet.com/articles/plant-facility-equipment/how-to-make-n95-masks/#_How_are_N95 (accessed on 16 July 2021).
18. Huber, T.; Goldman, O.; Epstein, A.; Stella, G.; Sakmar, T. Principles and practice of SARS-CoV-2 decontamination of N95 masks with UV-C. *Biophys. J.* **2020**, *120*, 2927–2942. [CrossRef]
19. U.S. Food Drug Administration. UV Lights and Lamps: Ultraviolet-C Radiation, Disinfection, and Coronavirus. Available online: https://www.fda.gov/medical-devices/coronavirus-covid-19-and-medical-devices/uv-lights-and-lamps-ultraviolet-c-radiation-disinfection-and-coronavirus (accessed on 16 July 2021).
20. Ozog, D.M.; Sexton, J.Z.; Narla, S.; Pretto-Kernahan, C.D.; Mirabelli, C.; Lim, H.W.; Hamzavi, I.H.; Tibbetts, R.J.; Mi, Q.S. The effect of ultraviolet C radiation against different N95 respirators inoculated with SARS-CoV-2. *Int. J. Infect. Dis.* **2020**, *100*, 224–229. [CrossRef]
21. Vo, E.; Rengasamy, S.; Shaffer, R. Development of a test system to evaluate procedures for decontamination of respirators containing viral droplets. *Appl. Environ. Microbiol.* **2009**, *75*, 7303–7309. [CrossRef]
22. Lindsley, W.G.; Martin, S.B., Jr.; Thewlis, R.E.; Sarkisian, K.; Nwoko, J.O.; Mead, K.R.; Noti, J.D. Effects of Ultraviolet Germicidal Irradiation (UVGI) on N95 Respirator Filtration Performance and Structural Integrity. *J. Occup. Environ. Hyg.* **2015**, *12*, 509–517. [CrossRef] [PubMed]
23. Ozog, D.; Parks-Miller, A.; Kohli, I.; Lyons, A.B.; Narla, S.; Torres, A.E.; Levesque, M.; Lim, H.W.; Hamzavi, I.H. The importance of fit testing in decontamination of N95 respirators: A cautionary note. *J. Am. Acad. Dermatol.* **2020**, *83*, 672–674. [CrossRef] [PubMed]
24. Sciences, S.L. The Advantages of Decontaminating with Vapor Phase Hydrogen Peroxide. Available online: https://www.sterislifesciences.com/resources/documents/technical-tips/the-advantages-of-decontaminating-with-vapor-phase-hydrogen-peroxide (accessed on 16 July 2021).

25. Saini, V.; Sikri, K.; Batra, S.D.; Kalra, P.; Gautam, K. Development of a highly effective low-cost vaporized hydrogen peroxide-based method for disinfection of personal protective equipment for their selective reuse during pandemics. *Gut Pathog.* **2020**, *12*, 29. [CrossRef] [PubMed]
26. Jatta, M.; Kiefer, C.; Patolia, H.; Pan, J.; Harb, C.; Marr, L.C.; Baffoe-Bonnie, A. N95 reprocessing by low temperature sterilization with 59% vaporized hydrogen peroxide during the 2020 COVID-19 pandemic. *Am. J. Infect. Control* **2021**, *49*, 8–14. [CrossRef]
27. Lore, M.B.; Heimbuch, B.K.; Brown, T.L.; Wander, J.D.; Hinrichs, S.H. Effectiveness of three decontamination treatments against influenza virus applied to filtering facepiece respirators. *Ann. Occup. Hyg.* **2012**, *56*, 92–101. [CrossRef]
28. Rockey, N.; Arts, P.J.; Li, L.; Harrison, K.R.; Langenfeld, K.; Fitzsimmons, W.J.; Lauring, A.S.; Love, N.G.; Kaye, K.S.; Raskin, L.; et al. Humidity and Deposition Solution Play a Critical Role in Virus Inactivation by Heat Treatment of N95 Respirators. *mSphere* **2020**, *5*. [CrossRef]
29. Bopp, N.; Bouyer, D.; Gibbs, C.; Nichols, J.; Ntiforo, C.; Grimaldo, M. Multicycle Autoclave Decontamination of N95 Filtering Facepiece Respirators. *Appl. Biosaf.* **2020**, *25*, 150–156. [CrossRef]
30. Anderegg, L.; Meisenhelder, C.; Ngooi, C.O.; Liao, L.; Xiao, W.; Chu, S.; Cui, Y.; Doyle, J.M. A scalable method of applying heat and humidity for decontamination of N95 respirators during the COVID-19 crisis. *PLoS ONE* **2020**, *15*, e0234851. [CrossRef]
31. Xiang, Y.; Song, Q.; Gu, W. Decontamination of surgical face masks and N95 respirators by dry heat pasteurization for one hour at 70 °C. *Am. J. Infect. Control* **2020**, *48*, 880–882. [CrossRef]
32. Pascoe, M.J.; Robertson, A.; Crayford, A.; Durand, E.; Steer, J.; Castelli, A.; Wesgate, R.; Evans, S.L.; Porch, A.; Maillard, J.Y. Dry heat and microwave-generated steam protocols for the rapid decontamination of respiratory personal protective equipment in response to COVID-19-related shortages. *J. Hosp. Infect.* **2020**, *106*, 10–19. [CrossRef]
33. Viscusi, D.; King, W.P.; Shaffer, R. Effect of Decontamination on the Filtration Efficiency of Two Filtering Facepiece Respirator Models. *J. Int. Soc. Respir. Prot.* **2007**, *24*, 93.
34. Fisher, E.M.; Williams, J.L.; Shaffer, R.E. Evaluation of microwave steam bags for the decontamination of filtering facepiece respirators. *PLoS ONE* **2011**, *6*, e18585. [CrossRef] [PubMed]
35. Zulauf, K.E.; Green, A.B.; Nguyen Ba, A.N.; Jagdish, T.; Reif, D.; Seeley, R.; Dale, A.; Kirby, J.E. Microwave-Generated Steam Decontamination of N95 Respirators Utilizing Universally Accessible Materials. *mBio* **2020**, *11*. [CrossRef] [PubMed]
36. Centers for Disease Control and Prevention. Chemical Disinfectants. Available online: https://www.cdc.gov/infectioncontrol/guidelines/disinfection/disinfection-methods/chemical.html (accessed on 16 July 2021).
37. Liao, L.; Xiao, W.; Zhao, M.; Yu, X.; Wang, H.; Wang, Q.; Chu, S.; Cui, Y. Can N95 Respirators Be Reused after Disinfection? How Many Times? *ACS Nano* **2020**, *14*, 6348–6356. [CrossRef] [PubMed]
38. Lendvay, T.S.; Chen, J.; Harcourt, B.H.; Scholte, F.E.M.; Lin, Y.L.; Kilinc-Balci, F.S.; Lamb, M.M.; Homdayjanakul, K.; Cui, Y.; Price, A.; et al. Addressing personal protective equipment (PPE) decontamination: Methylene blue and light inactivates severe acute respiratory coronavirus virus 2 (SARS-CoV-2) on N95 respirators and medical masks with maintenance of integrity and fit. *Infect. Control. Hosp. Epidemiol.* **2021**, 1–10. [CrossRef]
39. The NYC Health Department. COVID-19: Potential Decontamination Strategies for N95 Respirators. Available online: https://www1.nyc.gov/assets/doh/downloads/pdf/imm/n95-decontamination-strategies.pdf (accessed on 12 October 2021).
40. Heimbuch, B.K.; Kinney, K.; Lumley, A.E.; Harnish, D.A.; Bergman, M.; Wander, J.D. Cleaning of filtering facepiece respirators contaminated with mucin and Staphylococcus aureus. *Am. J. Infect. Control* **2014**, *42*, 265–270. [CrossRef]
41. Mills, D.; Harnish, D.A.; Lawrence, C.; Sandoval-Powers, M.; Heimbuch, B.K. Ultraviolet germicidal irradiation of influenza-contaminated N95 filtering facepiece respirators. *Am. J. Infect. Control* **2018**, *46*, e49–e55. [CrossRef]
42. Simmons, S.E.; Carrion, R.; Alfson, K.J.; Staples, H.M.; Jinadatha, C.; Jarvis, W.R.; Sampathkumar, P.; Chemaly, R.F.; Khawaja, F.; Povroznik, M.; et al. Deactivation of SARS-CoV-2 with pulsed-xenon ultraviolet light: Implications for environmental COVID-19 control. *Infect. Control. Hosp. Epidemiol.* **2021**, *42*, 127–130. [CrossRef]
43. Rathnasinghe, R.; Karlicek, R.F.; Schotsaert, M.; Koffas, M.A.; Arduini, B.; Jangra, S.; Wang, B.; Davis, J.L.; Alnaggar, M.; Costa, A.; et al. Scalable, effective, and rapid decontamination of SARS-CoV-2 contaminated N95 respirators using germicidal ultra-violet C (UVC) irradiation device. *medRxiv* **2020**. [CrossRef]
44. Golovkine, G.R.; Roberts, A.W.; Cooper, C.; Riano, S.; DiCiccio, A.M.; Worthington, D.L.; Clarkson, J.P.; Krames, M.; Zhang, J.; Gao, Y.; et al. Practical considerations for Ultraviolet-C radiation mediated decontamination of N95 respirator against SARS-CoV-2 virus. *PLoS ONE* **2021**, *16*, e0258336. [CrossRef]
45. Smith, J.S.; Hanseler, H.; Welle, J.; Rattray, R.; Campbell, M.; Brotherton, T.; Moudgil, T.; Pack, T.F.; Wegmann, K.; Jensen, S.; et al. Effect of various decontamination procedures on disposable N95 mask integrity and SARS-CoV-2 infectivity. *J. Clin. Transl. Sci.* **2020**, *5*, e10. [CrossRef] [PubMed]
46. Fischer, R.J.; Morris, D.H.; van Doremalen, N.; Sarchette, S.; Matson, M.J.; Bushmaker, T.; Yinda, C.K.; Seifert, S.N.; Gamble, A.; Williamson, B.N.; et al. Assessment of N95 respirator decontamination and re-use for SARS-CoV-2. *medRxiv* **2020**. [CrossRef]
47. Geldert, A.; Su, A.; Roberts, A.W.; Golovkine, G.; Grist, S.M.; Stanley, S.A.; Herr, A.E. Nonuniform UV-C dose across N95 facepieces can cause 2.9-log variation in SARS-CoV-2 inactivation. *medRxiv* **2021**. [CrossRef]
48. Weaver, D.T.; McElvany, B.D.; Gopalakrishnan, V.; Card, K.J.; Crozier, D.; Dhawan, A.; Dinh, M.N.; Dolson, E.; Farrokhian, N.; Hitomi, M.; et al. UV decontamination of personal protective equipment with idle laboratory biosafety cabinets during the COVID-19 pandemic. *PLoS ONE* **2021**, *16*, e0241734. [CrossRef]

49. Ludwig-Begall, L.F.; Wielick, C.; Jolois, O.; Dams, L.; Razafimahefa, R.M.; Nauwynck, H.; Demeuldre, P.-F.; Napp, A.; Laperre, J.; Thiry, E.; et al. "Don, doff, discard" to "don, doff, decontaminate"—FFR and mask integrity and inactivation of a SARS-CoV-2 surrogate and a norovirus following multiple vaporised hydrogen peroxide-, ultraviolet germicidal irradiation-, and dry heat decontaminations. *PLoS ONE* **2021**, *16*, e0251872. [CrossRef]
50. Kayani, B.J.; Weaver, D.T.; Gopalakrishnan, V.; King, E.S.; Dolson, E.; Krishnan, N.; Pelesko, J.; Scott, M.J.; Hitomi, M.; Cadnum, J.L.; et al. UV-C tower for point-of-care decontamination of filtering facepiece respirators. *Am. J. Infect. Control* **2021**, *49*, 424–429. [CrossRef]
51. Fisher, E.M.; Shaffer, R.E. A method to determine the available UV-C dose for the decontamination of filtering facepiece respirators. *J. Appl. Microbiol.* **2011**, *110*, 287–295. [CrossRef]
52. He, W.; Guo, Y.; Gao, H.; Liu, J.; Yue, Y.; Wang, J. Evaluation of Regeneration Processes for Filtering Facepiece Respirators in Terms of the Bacteria Inactivation Efficiency and Influences on Filtration Performance. *ACS Nano* **2020**, *14*, 13161–13171. [CrossRef]
53. Wigginton, K.R.; Arts, P.J.; Clack, H.L.; Fitzsimmons, W.J.; Gamba, M.; Harrison, K.R.; LeBar, W.; Lauring, A.S.; Li, L.; Roberts, W.W.; et al. Validation of N95 Filtering Facepiece Respirator Decontamination Methods Available at a Large University Hospital. *Open Forum Infect. Dis.* **2021**, *8*, ofaa610. [CrossRef]
54. Lin, T.H.; Tang, F.C.; Hung, P.C.; Hua, Z.C.; Lai, C.Y. Relative survival of Bacillus subtilis spores loaded on filtering facepiece respirators after five decontamination methods. *Indoor Air* **2018**, *28*, 754–762. [CrossRef]
55. Chen, P.Z.; Ngan, A.; Manson, N.; Maynes, J.T.; Borschel, G.H.; Rotstein, O.D.; Gu, F.X. Transmission of aerosols through pristine and reprocessed N95 respirators. *medRxiv* **2020**. [CrossRef]
56. Ou, Q.; Pei, C.; Chan Kim, S.; Abell, E.; Pui, D.Y.H. Evaluation of decontamination methods for commercial and alternative respirator and mask materials—View from filtration aspect. *J. Aerosol Sci.* **2020**, *150*, 105609. [CrossRef]
57. Ontiveros, C.C.; Sweeney, C.L.; Smith, C.; MacIsaac, S.; Bennett, J.L.; Munoz, S.; Stoddart, A.K.; Gagnon, G.A. Assessing the impact of multiple ultraviolet disinfection cycles on N95 filtering facepiece respirator integrity. *Sci. Rep.* **2021**, *11*, 12279. [CrossRef]
58. Kumar, A.; Kasloff, S.B.; Leung, A.; Cutts, T.; Strong, J.E.; Hills, K.; Vazquez-Grande, G.; Rush, B.; Lother, S.; Zarychanski, R.; et al. N95 Mask Decontamination using Standard Hospital Sterilization Technologies. *medRxiv* **2020**. [CrossRef]
59. Christie-Holmes, N.; Tyli, R.; Budylowski, P.; Guvenc, F.; Weiner, A.; Poon, B.; Speck, M.; Naugler, S.; Rainville, A.; Ghalami, A.; et al. Vapourized hydrogen peroxide decontamination in a hospital setting inactivates SARS-CoV-2 and HCoV-229E without compromising filtration efficiency of unexpired N95 respirators. *Am. J. Infect. Control* **2021**, *49*, 1227–1231. [CrossRef]
60. Oral, E.; Wannomae, K.K.; Connolly, R.; Gardecki, J.; Leung, H.M.; Muratoglu, O.; Griffiths, A.; Honko, A.N.; Avena, L.E.; McKay, L.G.A.; et al. Vapor H2O2 sterilization as a decontamination method for the reuse of N95 respirators in the COVID-19 emergency. *medRxiv* **2020**. [CrossRef]
61. Dave, N.; Pascavis, K.S.; Patterson, J.; Wallace, D.; Chowdhury, A.; Abbaszadegan, M.; Alum, A.; Herckes, P.; Zhang, Z.; Kozicki, M.; et al. Characterization of a novel, low-cost, scalable vaporized hydrogen peroxide system for sterilization of N95 respirators and other COVID-19 related personal protective equipment. *medRxiv* **2020**. [CrossRef]
62. Moschella, P.; Liao, W.; Litwin, A.; Foulk, J.; Anthony, J.; Player, M.; Chang, J.; Cole, C. Repeated vaporised hydrogen peroxide disinfection of 3M 1860 N95 mask respirators does not degrade quantitative fit performance. *Br. J. Anaesth.* **2021**, *126*, e125–e127. [CrossRef] [PubMed]
63. Russo, R.; Levine, C.; Grady, C.; Peixoto, B.; McCormick-Ell, J.; Block, T.; Gresko, A.; Delmas, G.; Chitale, P.; Frees, A.; et al. Decontaminating N95 respirators during the COVID-19 pandemic: Simple and practical approaches to increase decontamination capacity, speed, safety and ease of use. *J. Hosp. Infect.* **2021**, *109*, 52–57. [CrossRef]
64. Al-Hadyan, K.; Alsbeih, G.; Nobah, A.; Lindstrom, J.; Falatah, S.; Faran, N.; Al-Ghamdi, S.; Moftah, B.; Alhmaid, R. In-House Filtration Efficiency Assessment of Vapor Hydrogen Peroxide Decontaminated Filtering Facepiece Respirators (FFRs). *Int. J. Environ. Res. Public Health* **2021**, *18*, 7169. [CrossRef] [PubMed]
65. Levine, C.; Grady, C.; Block, T.; Hurley, H.; Russo, R.; Peixoto, B.; Frees, A.; Ruiz, A.; Alland, D. Use, re-use or discard? Quantitatively defined variance in the functional integrity of N95 respirators following vaporized hydrogen peroxide decontamination during the COVID-19 pandemic. *J. Hosp. Infect.* **2021**, *107*, 50–56. [CrossRef]
66. Lieu, A.; Mah, J.; Zanichelli, V.; Exantus, R.C.; Longtin, Y. Impact of extended use and decontamination with vaporized hydrogen peroxide on N95 respirator fit. *Am. J. Infect. Control* **2020**, *48*, 1457–1461. [CrossRef]
67. Beam, E.; Nesbitt, J.C.; Austin, M.D.; Ramar, K. Effect of vaporized hydrogen peroxide reprocessing on N95 respirators. *Infect. Control. Hosp. Epidemiol.* **2021**, *42*, 907–908. [CrossRef] [PubMed]
68. Veronique Greenwood; Quanta Magazine. Why Does Heat Kill Cells? Available online: https://www.theatlantic.com/science/archive/2017/05/heat-kills-cells/526377/ (accessed on 16 July 2021).
69. Kumar, A.; Kasloff, S.B.; Cutts, T.; Leung, A.; Sharma, N.; Vazquez-Grande, G.; Drew, T.; Laframboise, D.; Orofino, O.; Tanelli, J.; et al. Standard hospital blanket warming cabinets can be utilized for complete moist heat SARS-CoV2 inactivation of contaminated N95 masks for re-use. *Sci. Rep.* **2021**, *11*, 18316. [CrossRef] [PubMed]
70. Choi, Y.W.; Richardson, A.W.; Sunderman, M.; Mladineo, M.J.; Keyes, P.H.; Hofacre, K.C.; Middleton, J.K. Decontamination of SARS-CoV-2 contaminated N95 filtering facepiece respirators (FFRs) with moist heat generated by a multicooker. *Lett. Appl. Microbiol.* **2021**, *72*, 366–374. [CrossRef] [PubMed]

71. Oral, E.; Wannomae, K.K.; Gil, D.; Connolly, R.; Gardecki, J.A.; Leung, H.M.; Muratoglu, O.K.; Tsurumi, A.; Rahme, L.; Jaber, T.; et al. Efficacy of moist heat decontamination against various pathogens for the reuse of N95 respirators in the COVID-19 emergency. *medRxiv* **2020**. [CrossRef]
72. Daeschler, S.C.; Manson, N.; Joachim, K.; Chin, A.W.H.; Chan, K.; Chen, P.Z.; Tajdaran, K.; Mirmoeini, K.; Zhang, J.J.; Maynes, J.T.; et al. Effect of moist heat reprocessing of N95 respirators on SARS-CoV-2 inactivation and respirator function. *CMAJ* **2020**, *192*, E1189–E1197. [CrossRef]
73. Harskamp, R.E.; van Straten, B.; Bouman, J.; van Maltha-van Santvoort, B.; van den Dobbelsteen, J.J.; van der Sijp, J.R.; Horeman, T. Reprocessing filtering facepiece respirators in primary care using medical autoclave: Prospective, bench-to-bedside, single-centre study. *BMJ Open* **2020**, *10*, e039454. [CrossRef]
74. Czubryt, M.P.; Stecy, T.; Popke, E.; Aitken, R.; Jabusch, K.; Pound, R.; Lawes, P.; Ramjiawan, B.; Pierce, G.N. N95 mask reuse in a major urban hospital: COVID-19 response process and procedure. *J. Hosp. Infect.* **2020**, *106*, 277–282. [CrossRef]
75. Benboubker, M.; Oumokhtar, B.; Hmami, F.; Mabrouk, K.E.; Alami, L.E.; Arhoune, B.; Belahsen, M.F.; Aboutajeddine, A. Covid-19 respiratory protection: The filtration efficiency assessment of decontaminated FFP2 masks responding to associated shortages. *medRxiv* **2021**. [CrossRef]
76. Doshi, S.; Banavar, S.P.; Flaum, E.; Kulkarni, S.; Kumar, S.; Chen, T.; Bhattacharya, A.; Prakash, M. Applying Heat and Humidity using Stove Boiled Water for Decontamination of N95 Respirators in Low Resource Settings. *medRxiv* **2020**. [CrossRef] [PubMed]
77. Perkins, D.J.; Nofchissey, R.A.; Ye, C.; Donart, N.; Kell, A.; Foo-Hurwitz, I.; Muller, T.; Bradfute, S.B. COVID-19 global pandemic planning: Dry heat incubation and ambient temperature fail to consistently inactivate SARS-CoV-2 on N95 respirators. *Exp. Biol. Med.* **2021**, *246*, 952–959. [CrossRef]
78. Price, A.; Cui, Y.; Liao, L.; Xiao, W.; Yu, X.; Wang, H.; Zhao, M.; Wang, Q.; Chu, S.; Chu, L. Is the fit of N95 facial masks effected by disinfection? A study of heat and UV disinfection methods using the OSHA protocol fit test. *medRxiv* **2020**. [CrossRef]
79. Loh, M.; Clark, R.; Cherrie, J. Heat treatment for reuse of disposable respirators during Covid-19 pandemic: Is filtration and fit adversely affected? *medRxiv* **2020**. [CrossRef]
80. Nazeeri, A.I.; Hilburn, I.A.; Wu, D.-A.; Mohammed, K.A.; Badal, D.Y.; Chan, M.H.W.; Kirschvink, J.L. Ethanol-Drying Regeneration of N95 Respirators. *medRxiv* **2020**. [CrossRef]