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Strategies for managing N95 mask shortages at water resource recovery facilities during pandemics: a review

Rasha Maal-Bared and Jennifer Loudon

ABSTRACT

As the numbers of COVID-19 cases grew globally, the severe shortages of health care respiratory protective equipment impacted the ability of water resource recovery facilities (WRRFs) to acquire N95 masks for worker protection. While the Occupational Safety and Health Administration (OSHA) encourages WRRFs to conduct job safety assessments to mitigate risks from bioaerosols, it does not provide clear guidance on respiratory protection requirements, leaving the use of N95 masks across the industry non-standardized and difficult to justify. Strategies need to be developed to cope with shortages during pandemics, and these should take into consideration a WRRF's size and disinfection equipment available. Our objective is to provide an overview of respiratory protection-related practices recommended for health care professionals that apply to WRRFs (e.g., elimination, substitution, extended use, reuse, disinfection). Reviewed N95 mask disinfection strategies included using hydrogen peroxide, autoclaving, moist heat, dry heat, ultraviolet germicidal irradiation (UVGI), ethylene oxide, chlorine and ethanol. Of these, dry heat, autoclaving and UVGI present the most promise for WRRFs, with UVGI being limited to larger utilities. We recommend that WRRFs work closely with disinfection technology manufacturers, mask providers, health and safety staff and inspectors to develop suitable programs to cope with N95 mask shortages during pandemics.

Key words | COVID-19, disinfection, reuse, ultraviolet irradiation, utility management, worker safety

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HIGHLIGHTS

- During the COVID-19 pandemic, PPE shortages impacted utility supply chains.
- N95 mask disinfection strategies investigated include hydrogen peroxide, autoclaving, moist heat, dry heat, UV and other less suitable strategies. Of these studies, dry heat, autoclaving and UVGI are the most promising.
- Utility managers should investigate reduction, elimination, substitution, extended use and reuse of N95 masks where possible.

WATER RESOURCE RECOVERY FACILITIES AND COVID-19

Introduction

Wastewater treatment is a critical service for the maintenance of a sustainable and healthy society. Utilities have a long history of preparing for certain types of emergencies and hazards (e.g., natural disasters, climate change, power interruptions, cyber-attacks). However, health emergencies, like the current coronavirus disease 2019 (COVID-19) pandemic, present unique and unforeseen challenges: social distancing, potential quarantines, workforce and supply chain disruptions and travel restrictions. These impact many aspects of day-to-day utility operation and complicate previously implemented emergency response and business continuity plans.

As the numbers of COVID-19 cases grew globally, severe shortages of essential health care supplies and personal protective equipment (PPE) were reported, especially for respiratory protection equipment and N95 masks

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(Carrillo *et al.* 2020; Rimmer 2020). In turn, it became increasingly difficult for many water resource recovery facilities (WRRFs) to procure respiratory protection for their employees and justify the need for respiratory protection in light of lacking standards. Strategic and holistic strategies need to be developed to prepare for and cope with shortages during pandemics (AWWA 2020; Hawkins & Kricun 2020). These strategies should take into consideration both the resources available in wastewater laboratories where disinfection will be performed and the differences between large and small utilities.

The objective of this paper is to provide an overview of respiratory protection-related practices recommended by the Centers for Disease Control and Prevention (CDC) for health care professionals that apply to WRRFs and that most wastewater laboratories can implement to support plant and field operations. Strategies include elimination, substitution, extended use, reuse and possibly disinfection of N95 masks while supply chain shortages persist. Considering that health care professionals are considered at high risk for COVID-19 occupational infection and that the likelihood of COVID-19 transmission through wastewater is still considered low (Occupational Safety and Health Administration (OSHA) 2020), approved and recommended PPE practices that are sufficient for health care professional protection should also be sufficient to protect wastewater workers from SARS-CoV-2 and other pathogens found in wastewater and WRRF bioaerosols.

Challenges in acquiring respiratory protective equipment for WRRF workers

In March 2020, the American Water Works Association (AWWA) surveyed 534 utilities to assess the impacts of COVID-19 on utility management and actions being taken to manage risks. The AWWA survey showed that 63% of utilities in Canada and 59% of utilities in the USA reported either currently experiencing disruptions in PPE supply chains or anticipating disruptions within the next month (AWWA 2020). This is problematic since handling untreated or partially treated wastewater is known to carry an inherent risk of exposure to various bacterial, viral and protozoan pathogen (Water Environment Federation 2013) and since the risk of acquiring occupational infections among wastewater and collection system workers remains poorly understood (LeChevallier *et al.* 2019).

In its *Guidance for Reducing Health Risks to Workers Handling Human Waste or Sewage*, the CDC states that workers handling human waste or sewage should be provided proper PPE, training on how to use PPE effectively and hand-washing facilities. The PPE required includes: eye protection to protect from splashes of human waste or sewage; protective face mask or splash-proof face shield to protect nose and mouth from splashes of human waste or sewage; liquid-repellent coveralls to keep human waste or sewage off clothing; waterproof gloves to prevent exposure to human waste or sewage and to minimize fecal – oral and fomite contamination; and rubber boots to prevent exposure to human waste or sewage (CDC 2017).

The CDC and the OSHA do not include clear recommendations on respiratory protection requirements for wastewater workers. Since respiratory exposure to biological hazards varies by task, process and facility, respiratory protection required at WRRFs is much more subjective and less defined. OSHA encourages utility managers to conduct job safety (or hazard) assessments that systematically identify each task in a job, define the potential hazards workers are exposed to, and outline critical safety practices to mitigate risk to workers (Water Environment Federation 2013; LeChevallier *et al.* 2019). This is partially due to the regulators' lack of understanding of what work at a WRRF entails, including the potential routes by which workers could be exposed to infectious agents and the potential magnitude of exposure along each potential route (LeChevallier *et al.* 2019). As a result, the use of respiratory protection across the industry is non-standardized (Water Environment Federation 2020) and justification for N95 mask acquisition is lacking. The lack of access to N95 masks presented additional challenges for utility management during the COVID-19 pandemic since many wastewater workers experienced heightened risk perception and fear.

Various authors have reported the presence of human pathogens in bioaerosols at WRRFs (Carducci *et al.* 2000; O'Hara & Rubin 2005; Haas *et al.* 2010; Uhrbrand *et al.* 2011, 2017; Brisebois *et al.* 2018; Carducci *et al.* 2020). LeChevallier *et al.* (2019) recommend the use of a job safety assessment to determine the need for respiratory protection when performing collection system vacuum (also called jetter or hydrovac) truck operations, routine high pressure washing in tanks and basins, active pump and line maintenance, tank entry for maintenance activities, bar screen cleaning, and compost and Class B biosolids handling. However, when known exposure to respiratory pathogens is likely to occur (e.g., during live sewer entry or live sewer pipe repair work) respiratory protection should be required (LeChevallier *et al.* 2019). Thus, respiratory protection is needed for various tasks.

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The WRRF wastewater laboratory

Wastewater laboratories play a critical role in ensuring that discharges from WRRFs meet appropriate regulatory standards to protect receiving waters (Aldenhoff & Ernest 1983). Analytical tests performed by wastewater laboratories support plant process monitoring and optimization, sludge recycling, residuals and solids treatment, plant asset management and various research efforts. Some wastewater laboratories are involved in permitting, inspecting, sampling and testing effluents from significant industrial users in the collection system to determine that the wastewater discharge meets local discharge pre-treatment limits. Wastewater laboratories charge permit fees, fines, surcharges and monitoring costs from various industries, commercial customers and other treatment plants throughout the service area, making them generate revenue for many large WRRFs. Specialized testing, subject matter experts and decontamination equipment are all usually housed in the wastewater laboratory at WRRFs.

Much like operators, maintenance and utilities crews, laboratory personnel are required to come into close contact with a variety of wastewater and sludge samples at various stages of treatment on a daily basis (Aldenhoff & Ernest 1983; Water Environment Federation 2013; Spellman & Welsh 2017). Analysts often create conditions that result in the concentration and/or amplification of infectious organisms on purpose or inadvertently. Studies have shown that even simple procedures like serial dilutions and plating can result in the generation of small amounts of aerosols both by experienced and inexperienced laboratory analysts (Pottage *et al.* 2014). Laboratory-acquired infections (LAI) are well documented and an occupational hazard for staff working in laboratories (Sewell 1995; Ng *et al.* 2011; Coelho & Díez 2015). In Canada, suspected LAI in any licensed laboratory must be reported to the Public Health Agency of Canada's Biosafety and Biosecurity Center (Public Health Agency of Canada 2018). Laboratory workers at WRRFs must be aware of this potential for infection (Water Environment Federation 2013; Spellman & Welsh 2017) and use regular PPE to limit worker exposure to chemical and microbiological contaminants (Coelho & Díez 2015).

Laboratory worker PPE includes all clothing and work accessories designed to protect employees from chemical, physical and microbiological workplace hazards (Lab Manager 2009). When working in a lab, PPE is almost always necessary. Lab coats, gloves, and safety eyewear are the basic PPE needed. A lab coat or other protective clothing should be worn whenever chemicals or biological materials are handled (Spellman & Welsh 2017). Carefully selected gloves for the hazard present should be worn whenever handling hazardous materials (e.g., chemical-resistant, heat-resistant). Safety glasses and goggles provide protection against impact hazards, while chemical splash goggles provide the best protection against chemical splash as well as preventing analysts from touching their eyes. Face shields protect the entire face from projectiles and offers some protection from splashes (Lab Manager 2009). Some sources state that respiratory protection may be needed depending on the task and hazards (Lab Manager 2009; Water Environment Federation 2013; Spellman & Welsh 2017). Similar to other WRRF workers, the conditions that necessitate usage of respiratory protection at wastewater laboratories due to exposure to bioaerosols are not defined partially due to lack of familiarity with lab procedures and tasks even within the WRRF itself.

Differences between small and large utilities

The size of a WRRF and its corresponding workforce tends to correlate with the number of customers served in the area. As a result, metropolitan and urban centres are often served by larger utilities relative to smaller, more remote communities. Larger utilities will have more specialized personnel and larger inventories, financial resources, purchasing power and access to suppliers (Hawkins & Kricun 2020). Similarly, many of these WRRF traits can be seen in their corresponding laboratories. Laboratories at large WRRFs are more likely to be staffed by technicians and scientists who were trained in chemistry, biology and environmental sciences (Spellman & Welsh 2017). They are also more likely to have complex analytical instruments, elaborate quality assurance and quality control programs, larger capital budgets, and local safety protocols developed in-house to manage and mitigate risk (Aldenhoff & Ernest 1983; Spellman & Welsh 2017).

Interestingly, the water sector is dominated by thousands of smaller water utilities that often rely on a handful of critical personnel with a diverse range of duties (including laboratory analyses) and have limited financial resources or on-site inventory (Hawkins & Kricun 2020). These smaller utilities tend to serve 10,000 population equivalents or less, and are often located in rural, remote and tourist communities (Tsagarakis *et al.* 2000). Additionally, smaller WRRFs operationally experience more pronounced load fluctuations, operation and maintenance problems and per capita costs, thus making operation and laboratory analysis more challenging for operators (Boller 1997). Training

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operators and turnover at small utilities has been a challenge for decades (Tsagarakis *et al.* 2000). As a result of these differences, the N95 mask reuse and disinfection strategies that may work for some large WRRFs and their laboratories may not be practical, possible or realistic for smaller WRRFs, and vice versa.

A PRIMER IN RESPIRATORY PROTECTION EQUIPMENT

Respiratory protection equipment is a type of PPE that prevents the wearer from inhaling dangerous substances such as particulates, aerosols, vapors and gases. It can be tight-fitting, such as a half-mask (covers the mouth and nose like an N95 mask) or a full facepiece (covers the face from the hairline to below the chin). It can also be loose-fitting, such as surgical masks. Respiratory protective equipment works by filtering particles out of the air (e.g., filtering facepiece respirators; FFRs), by purifying the air through the removal of hazardous chemicals using chemical reactions in cartridges (e.g., chemical cartridge respirators or powered air purifying respirators) or by providing workers with an external clean air source (e.g., self-contained breathing apparatuses) (OSHA 2002).

Respirators that filter out particulates can also be broken down into three categories (CDC 2020b): (1) disposable or filtering facepiece respirators, where the entire respirator is discarded when it becomes unsuitable for further use due to excessive resistance, sorbent exhaustion, or physical damage; (2) reusable or elastomeric respirators, where the facepiece is cleaned and reused but the filter cartridges are discarded and replaced when they become unsuitable for further use; and (3) powered air purifying respirators, where a battery-powered blower moves the air flow through the filters.

The National Institute for Occupational Health and Safety (NIOSH) recommends the use of N95 masks for the protection from particles <100 nm in size, such as viruses. N95 FFRs are the PPE most commonly used to control exposure to airborne infections though their effectiveness is highly dependent upon proper fit and use. Thus, respiratory protection equipment must always be used in combination with administrative and engineering interventions and after examining the possibility of elimination or substitution of exposure (OSHA 2002; CDC 2020c). Respiratory protection programs at WRRFs will include fit testing and training of each worker in the use, maintenance, and care of the respirator (CDC 2020b).

N95 masks are expected to remove at least 95% of particulates that are 0.3 μm or larger in aerodynamic diameter. An N95 respirator is one of nine types of disposable particulate respirators. Other FFRs exist that vary in effectiveness. For example, an N100 is expected to remove at least 99.97% of particulates in the same size range. Respirators in this family are rated as N, R, or P for protection against oils. This rating is important in industry because some industrial oils can degrade the filter performance and alter fit. Respirators are rated '**N**' if they are **N**ot resistant to oil, '**R**' if somewhat **R**esistant to oil, and '**P**' if oil **P**roof. Thus, there are nine types of disposable particulate respirators: N-95, N-99, and N-100; R-95, R-99, and R-100; and P-95, P-99, and P-100 (CDC 2020b).

Europe uses a different naming system based on two different standards. The filtering face piece (FFP) score comes from EN standard 149:2001 and EN 143 standard covers P1/P2/P3 ratings. Both standards are maintained by the European Committee for Standardization (CEN). In this system, FFP1, FFP2 and FFP3 eliminate at least 80, 94 and 99% of particles with a diameter of 0.3 μm or larger, respectively (European Commission for Standardization 2000, 2009).

STRATEGIES TO DEAL WITH THE N95 MASK SHORTAGES AT WRRFS

Reduce, eliminate and substitute use

It is the responsibility of utility managers to consider the preferential use of engineering and administrative controls before using PPE to protect staff. Additionally, many WRRFs have moved to minimum staffing during the COVID-19 pandemic. Thus, it seems possible to minimize the number of employees who need to use respiratory protection through the identification and prioritization of critical and/or urgent work, improved scheduling practices, negotiation of regulatory requirements or performance targets with regulating bodies and stakeholders, and coordination of work with customers and contractors on- and offsite. Live or pressurized pumps, valves, pipes and instrumentation could be taken offline to reduce risk of splashing and aerosol generation during task performance. Working with plant maintenance and engineering to increase the number of air exchanges in enclosed areas where aerosols are generated through heating, ventilation and air conditioning (HVAC) system controls may also be a possibility. Ideally, all high aerosol generating procedures would be completed in one

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shift, since NIOSH states that respirators can function within their design specifications for 8 hours of continuous or intermittent use (CDC/NIOSH 2020).

Similarly, in the laboratory, some procedures (e.g., vacuum filtrations for total suspended solids or membrane filtration testing) can be moved into fume hoods or preferably into biosafety cabinets, which are more protective but less likely to be found in a small laboratory. Preferentially purchasing equipment and consumables that reduce aerosol generation in the future to limit exposure to other pathogens found in wastewater is also beneficial (e.g., pipette tips, centrifuges with double containment to avoid vial breakage). HVAC system adjustments may also be a possibility, provided they do not impact laboratory analyses negatively through dust or contaminant resuspension. Additional considerations should include discussion of analytical and sampling frequencies with regulating bodies, examining sample preservation practices, and reorganizing internal and external sample receipt and workflow to complete aerosol generating procedures in one shift, if possible.

Many WRRF workers, including laboratory staff, are fit tested for other classes of FFR that are not disposable or single use. In those cases, the use of alternatives to N95 respirators (e.g., other classes of FFR, elastomeric half-mask and full facepiece air purifying respirators, powered air purifying respirators) is feasible. This is especially applicable to small laboratories, where the operator also performs laboratory analyses as they tend to be fit tested for plant work. It is also important to prioritize the use of masks for workers who interact with the public or have to share vehicles or small spaces for sample collection or performing maintenance activities, where social distancing is not possible. Figure 1 outlines possible considerations for utility managers to reduce, eliminate or substitute N95 mask use at utilities.

Extended use and limited reuse

Extended use in public health is used to refer to the practice of wearing the same N95 respirator for repeated close contact encounters with several patients, without removing the respirator between patients (CDC/NIOSH 2020; Public Health England 2020). In a utility environment, this would be similar to the continuous use of an N95 mask to complete multiple tasks with risk of exposure to bioaerosols without taking the mask off. This can be accomplished through changes in scheduling and workflows and by understanding the nature of the tasks undertaken by the employees (e.g., activities, hazards, frequency, duration), as well as the tasks' safety, reporting and operational requirements. In

- Can we work with staff to identify practices that generate aerosols or carry perceived risk? Are staff trained to perform these with minimal exposure? Can they be trained virtually if need be?
- Do staff know the appropriate engineering and administrative controls in place? Are these included in a standard operating procedure or work safe plan?
- Can we work with the plant, regulators, customers and staff to prioritize critical work, streamline workflows, improve scheduling, negotiate regulatory and performance targets and conduct high bioaerosol generating tasks on the same shift by fewer staff?
- Can we take live or pressurized valves, pumps, pipes and instrumentation offline before conducting repairs or maintenance tasks?
- Can we move some work practices into controlled environments where exposure is limited (e.g., hoods, biosafety cabinets)? Can we preserve samples to reorganize workflow in the laboratory?
- Can we work with plant maintenance to increase the number of air exchanges in areas of the laboratory where the generation of bioaerosols is a concern?
- How many employees are trained and fit tested for other, non-disposable FFR?
- Are we prioritizing employees who interact with the public, making sure they have access to respiratory protection first, based on known risk of transmission?
- Can we discuss sampling and analytical frequency with local regulating bodies to reduce frequency or change reporting requirements?
- Can we share lessons learned from our strategies to prepare for future pandemics?

Figure 1 | Potential considerations for utility managers to reduce, eliminate or substitute N95 mask use at the WRRF.

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the laboratory, this also requires the manager to show leadership in working with customers to stage arrival of high-risk samples (e.g., drainage bylaws, combined sewer overflows, raw plant influent) that may contain respiratory pathogens. This practice could benefit long-term lab planning and reduce exposure of lab staff to other respiratory pathogens and LAI in general.

Reuse in public health refers to the practice of using the same N95 respirator for multiple encounters with patients but removing ('doffing') it after each encounter. The respirator is stored between encounters to be put on ('donned') again prior to the next encounter. This is referred to as limited reuse because restrictions are in place that limit the number of times the same FFR is reused, due to its impact on fit and thus on protective qualities (CDC/NIOSH 2020; Public Health England 2020). In a utility environment, this would refer to using the same respirator for multiple shifts or tasks, taking the PPE off and storing it between uses. Good hygiene practices become extremely important here. During storage periods, workers should hang respirators or store them in a designated storage area in a clean, breathable container. The number of times a mask can be reused should be based on manufacturer's recommendations. 3M has issued a technical bulletin that recommends using the CDC guideline of limiting mask reuse to no more than five uses per device (3M 2020). Prior to putting the mask on again, fit must be tested.

Similar to health care guidelines, reuse is not advised if the mask is soiled, damaged, or hard to breathe in. It is only advisable for masks with elastic ear hooks since tie-on face masks are less suitable because they are more difficult to remove. Reuse is also not advisable for masks that deform once worn, thus making passing the seal check unlikely. The use of a face shield over the N95 mask is an option reducing the contamination of the exterior of the mask in medical settings. This practice is already in place at many utilities during tasks with high potential for splashing but is unnecessary in the laboratory environment unless deemed important through the job safety assessment.

A standard operating procedure should be developed to cover how to safely doff, store and don the fluid-resistant surgical masks and disposable respirators (e.g., FFP3, FFP2, N95, N100) if reuse is planned. It should include, but is not limited to, the following steps (CDC/NIOSH 2020; Public Health England 2020; Rimmer 2020):

- A clean, breathable, sealable bag or container marked with the wearer's name should be ready for use and document the number of reuses (e.g., paper containers or bags).
- Before removing the mask, hand hygiene should be performed.
- The ear hooks must be used to remove the mask without causing cross contamination since the outside of the mask is contaminated and the inside must remain clean.
- The face mask should be carefully folded so the outer surface is held inward onto itself to reduce likely contact with the outer surface during storage.
- The folded mask should be stored in the clean, prepared sealable bag or container.
- Hand hygiene should be performed after removing the face mask.
- A fit check should be performed each time a respirator is donned if it is reused.

DISINFECTION AND STERILIZATION OF N95 MASKS: A REVIEW OF THE LITERATURE

Definitions

Sterilization destroys or eliminates all forms of microorganisms using physical or chemical means. Steam under pressure (e.g., autoclaving), dry heat (e.g., ovens), ethylene oxide (EtO) gas, hydrogen peroxide (as vapor, plasma, fogging), ozone, ultraviolet germicidal irradiation (UVGI) and liquid chemicals are the principal sterilizing agents used in health care facilities (CDC 2008). ***Disinfection*** describes a process that eliminates many or all pathogenic microorganisms on inanimate objects, except bacterial spores (CDC 2008). In health care settings and at the wastewater laboratory, objects and surfaces are usually disinfected using liquid chemicals (such as 0.5% bleach or 70% ethanol). Health care settings also use wet pasteurization (i.e., moist heat), which is less common at WRRFs. In many cases, processes used for sterilization can be used for disinfection instead by altering contact time. ***Decontamination*** refers to the reduction in levels of microbial contamination to levels assumed to be safe and resulting in negligible risk of infection. Sterilization and disinfection are both forms of decontamination (CDC 2008).

In health care settings, disinfection and sterilization are essential for ensuring that medical and surgical instruments do not transmit pathogens to patients. Failure to properly disinfect or sterilize equipment carries not only risk associated with breach of host barriers but also risk of person-to-person transmission (e.g., hepatitis B virus) and transmission of environmental pathogens (e.g., *Pseudomonas aeruginosa*). But even in health care settings, sterilization of all patient-care items is unnecessary. Health care policies

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must identify, primarily on the basis of the items' intended use, whether cleaning, disinfection, or sterilization is indicated. As a result, health care professionals have access to many disinfection and sterilization methods that are neither practical nor accessible to WRRFs and their wastewater laboratories (CDC 2008).

The only areas in WRRFs where sterilization is necessary are the wastewater laboratories for microbiological analyses. Any instruments, equipment, vessels, media or reagents that come in contact with microbiological samples must be sterile. Additionally, any waste produced from these analyses must be decontaminated in accordance with institutional and regulatory waste disposal guidelines. As a result, most wastewater laboratories have autoclaves. Some laboratories have biosafety cabinets with UVGI capacity and microwaves. Additionally, any laboratory that runs wastewater effluent compliance testing (e.g., total suspended solids, volatile suspended solids) must have an oven. To our knowledge, no wastewater laboratories have hydrogen peroxide vapor or ozone generators. Access to specialized moist heat or wet pasteurization equipment is also unlikely.

Surface, PPE and equipment disinfection is common practice throughout WRRFs. Disinfection is usually performed using various liquid disinfectants (e.g., bleach, ethanol), but some WRRFs use disinfecting wipes, especially for field work. Some regularly used and highly efficacious disinfectants in health care cannot be used in wastewater laboratories due to interference with required laboratory testing (e.g., quaternary ammonium interferes with several types of nitrogen analysis).

When considering disinfection of respirators for the WRRF, the 3M Safety Center (2020) notes the importance of evaluating the impact of the chosen method on: inactivation of target organism (such as SARS-CoV-2), changes in respirator performance based on filtration capacity, charge retention, respirator fit and possible impacts on the safety of the person wearing the PPE due to off-gassing. The CDC has posted an extensive review of the literature on PPE disinfection with a focus on respiratory pathogens in health care settings (CDC 2020a). We evaluate the same literature from a WRRF perspective in Table 1.

Hydrogen peroxide

The use of hydrogen peroxide for N95 mask disinfection has been investigated extensively in the literature since the beginning of the COVID-19 pandemic (Fischer *et al.* 2020; Grossman *et al.* 2020; John *et al.* 2020; Kenney *et al.* 2020; Kumar *et al.* 2020; Schwartz *et al.* 2020; Wigginton *et al.* 2020). Despite this, the use of hydrogen peroxide is fairly limited to large health care facilities and university hospitals (Zulauf *et al.* 2020) and is not likely to be viable for WRRFs or their wastewater laboratories. As a result, hydrogen peroxide technologies will be not be reviewed in detail or included in the summary in Table 1.

Hydrogen peroxide technologies fall into three categories: hydrogen peroxide gas plasma treatment (HPGP), hydrogen peroxide fogging, and vaporized hydrogen peroxide (VHP). VHP tends to be the most frequently examined in health care settings due to the availability and use of its equipment for the fumigation of patient rooms in hospitals (Kenney *et al.* 2020). It is currently the only disinfection process for N95 respirators approved by Health Canada and the US Food and Drug Administration (US FDA) due to its broad spectrum effectiveness against enveloped and non-enveloped viruses (Nocospray Disinfection Systems 2020). Meanwhile, use of HPGP for N95 mask disinfection has been reported to result in significant damage to most masks tested after two or more cycles, likely due to the high required concentration of liquid hydrogen peroxide and the strongly charged ionized vapor state of this device neutralizing the N95 mask's electrostatic charge, thus no longer trapping airborne particulates (Kumar *et al.* 2020; Wigginton *et al.* 2020). It is advisable to review manufacturer recommendations and factsheets to determine the suitability of some technologies for N95 mask disinfection guidelines (Advanced Sterilization Products 2020).

UV germicidal irradiation

UVGI is one possible method for respirator disinfection at large WRRFs. UVGI experiments usually target efficacy of UV-C at 254 nm, which corresponds with irradiation capacities of regular biosafety cabinets, or pulsed xenon UV technologies (UV-PX) which covers both UV-B and UV-C at 200–315 nm (3M 2020). Pulsed xenon UV is uncommon at most WRRF laboratories and was reported to be less effective than UV-C lamps (Wigginton *et al.* 2020). While larger WRRF laboratories tend to have biosafety cabinets, most small laboratories only have small UV lamps (used for enumerating total coliforms and E. coli using defined substrate technologies that result in fluorescence), making this method unsuitable for them. UVGI is also limited by inherent shadow effects of the light-source, variability in dosages due to bulb age and differing platform constructions (Mills *et al.* 2018).

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Table 1 | Summary of studies investigating the use of N95 disinfection and their application for wastewater labs and WRRFs

Option	SARS-CoV-2 evidence	Procedure	Impacts on				Suitability for		Challenges
			Inactivation	Filtration capacity	Fit	Off-gas	Large lab	Small lab	
Autoclaving	Harskamp *et al.* (2020)	17-min steam sterilization cycle at 121 °C for three cycles	Not tested	Pass	Pass	None	Yes	Yes	Procuring sterilization pouches
	Kumar *et al.* (2020)	15-min steam sterilization cycle at 121 °C for 10 cycles for pleated fabric masks	5–6-log reductions		Pass	None	Yes	Yes	Molded masks were immediately damaged after one cycle
	3M (2020); STERIS (2020)	STERIS system at 65 ± 5 °C and 50–80% relative humidity (RH) for 30 min for 10 rounds	Not tested	Pass	Pass	None	No	No	Approved for 3M models 1860, 8210, 1804, 1870+ and requires one pouch/FFR
	Wigginton *et al.* (2020)	15-min steam sterilization cycle at 121 °C	Visibly damaged			None	No	No	
Moist heat	Liao *et al.* (2020)	10-min steam treatment over a beaker at 125 °C for five cycles	2-log reductions	Pass	Not tested	None	Yes	Yes	Polypropylene melting point about 130–170 °C
	Wigginton *et al.* (2020)	Drying cycle of industrial washer at 80–82 °C at >60% RH for 30 min	1.4–6.8-log reductions	Not shown			Yes	Yes	
Microwave	Zulauf *et al.* (2020)	3 min at 1,100 W with direct steam exposure up to 20 rounds	6-log reductions	Pass	Pass	None	Yes	Yes	May require exposure to steam directly; variable power setting and metal exposure
Dry heat	Fischer *et al.* (2020)	70 °C oven for 60 min for two rounds	5-log reductions	Pass	Pass	None	Yes	Yes	Possible melting of N95 mask metal parts
	Liao *et al.* (2020)	75 °C oven for 30 min at 0–30% RH for 20 rounds	2-log reductions	Pass	Not tested	Safe	Yes	Yes	75 °C for 30 min should be safe and humidity had no impact
	Wigginton *et al.* (2020)	Industrial washer drying cycle at 80 °C for 15 min at 8% RH for 10 cycles	1–2-log reductions	Pass	Not tested	Safe	Yes	Yes	Higher reductions are preferable
UV-C (254 nm)	Fischer *et al.* (2020)	UV lamp 260–285 nm at 1.98 J/cm^2 for 60 min for three rounds	5-log reductions	Pass	Pass	None	Yes	No	Slow but effective
	Lindsley *et al.* (2015)	15 W T-150 254 nm UV-C lamp at 0, 120, 240, 470, or 950 J/cm^2	Not tested	Fail	Not tested	None	No	No	Cycles will be limited by the respirator model and the UVGI dose
	Lowe *et al.* (2020)	254 nm UV-C at 200 μW/cm^2 for 15 min resulting in 2–5 mJ/cm^2	6-log reductions	Not tested	Not tested	None	Yes	No	Some safety concerns related to radiation and reflective surfaces
	Liao *et al.* (2020)	254 nm UV-C for 30 min at 8 W for 10 cycles	2-log reductions	Pass	Not tested	None	Yes	No	Achieving uniform intensity distribution and dose determination

(*continued*)

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Table 1 | continued

Option	SARS-CoV-2 evidence	Procedure	Impacts on				Suitability for		Challenges
			Inactivation	Filtration capacity	Fit	Off-gas	Large lab	Small lab	
	3M (2020)	254 nm UV-C exposure at 1 J/cm^2 (cumulative exposure of 10 J/cm^2 on each side) for 10 cycles	Not tested	Pass	Pass	None	Yes	No	3M models 1860, 8210, 1804
Chlorine	Liao *et al.* (2020)	2% chlorine spray for 5 min and air drying once	Not tested	Fail	Not tested	None	No	No	
Ethanol	Fischer *et al.* (2020)	70% ethanol for 10 min for one round	5-log reductions	Fail	Fail	None	No	No	Fast but impacts performance
	Liao *et al.* (2020)	75% ethanol immersion and air drying	2-log reductions	Fail	Not tested	Possible	No	No	
Ethylene oxide	Kumar *et al.* (2020)	1 hr exposure and 12 hours aeration time for three rounds	6-log reductions	Not tested	Pass	Not tested	No	No	Toxicity and flammability
	Wigginton *et al.* (2020)	1 hour exposure at 55 °C at 45% RH, 12 hours aeration and 15 hours total cycle time	5.8-log reductions	Not tested	Not tested	Not tested	No	No	Toxicity to wearer of concern

Hydrogen peroxide and pulsed xenon UV will not be included due to their unavailability at WRRFs.

Various studies have tested the impacts of high dose UVGI on mask integrity (Viscusi *et al.* 2009; Lindsley *et al.* 2015; Lowe *et al.* 2020; Price & Chu 2020). Lindsley *et al.* (2015) investigated the impacts of high UVGI doses (120–950 J/cm^2) on respirators and found that UVGI exposure had little effect on particle penetration and flow resistance. However, UVGI exposure had a significant effect on the strength of the layers of respirator material, reducing it by more than 90% in some cases. UVGI had less of an effect on the respirator straps and a reduction in dose reduced the breaking strength of the straps by 20–51% (Lindsley *et al.* 2015). They highlighted that the doses they used for this study were specifically attempting to degrade masks. Similarly, common irradiation doses are almost three magnitudes lower than the results reported by Lowe *et al.* (2020), who suggested that a 6-log reduction in conservative surrogate organisms could be achieved at 2–5 mJ/cm^2. These authors set UVGI sensor exposure at 60 and 300 mJ/cm^2 and reminded readers that the UV sensor readings of 60 mJ/cm^2 represent a total mask exposure dose of 180–240 mJ/cm^2 and a sensor reading of 300 mJ/cm^2 (15-min total cycle time) represents a total mask exposure dose of 900–1,200 mJ/cm^2 depending on mask placement on the mask hanging lines.

Fischer *et al.* (2020) evaluated the use of gamma irradiation (260–285 nm, UV-C power 550 μW/cm^2) and found that N95 masks maintained acceptable performance after three rounds of decontamination. At 60 min, the masks had been exposed to 1.98 J/cm^2. They report that this aligns with the CDC estimate and previous work by Mills *et al.* (2018) that suggests a 1 J/cm^2 dose can achieve 3-log reductions in viable viral loads. It also aligns with 3M recommendations that suggest the use of UV-C exposure at 254 nm to disinfect models 1,860, 8,210, 1,804 at 1 J/cm^2 for 10 cycles, resulting in a cumulative exposure of 10 J/cm^2 on each side and a maximum 100 J/cm^2 lifetime exposure (3M 2020). Liao *et al.* (2020) reported no significant impacts on filtration capacity and pressure drop with UVGI sterilization at 254 nm (8 W) for 30 min for 10 cycles, but state that deterioration was seen after 20 cycles. They suggested this agreed with previous findings that found SARS-CoV-1 was inactivated at 3 mJ/cm^2 but cautioned that UV-C light areal intensity distribution is ununiform inside the cabinet and exact dose determination is challenging (Liao *et al.* 2020).

In summary, UV irradiation kills the virus more slowly compared to VHP but preserves comparable respirator function, thus making it a viable candidate (Fischer *et al.* 2020). Researchers have cautioned that UVGI dose and mask

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model may determine the number of decontamination cycles that can be run.

Autoclaving

Various studies have reported the efficacy of autoclaving and steam treatments to sterilize FFR. Harskamp *et al.* (2020) examined the impacts of a 17-min steam sterilization cycle at 121 °C (full cycle length 34 min) on FFP2 (with and without exhalation valve, similar to P2) and an FFP3 (similar to N99). They found that the FFR filtration capacity, seal check and pressure resistance did not change significantly after autoclaving for three cycles (Harskamp *et al.* 2020). The specific autoclave used in this study has a cycle for solids composed of rubber and delicate solids.

These results correspond with previous findings by Lin *et al.* (2017), who used a 15-min cycle at 121 °C to sterilize N95 masks and reported that this disinfection method was effective and did not impact performance (Lin *et al.* 2017). Kumar *et al.* (2020) investigated autoclaving as well but reported different results. They tested a standard STERIS AMSCO Lab 250 model (STERIS Life Sciences, Mentor, OH) with a peak temperature of 121 °C for 15 min (full cycle length 40 min). They reported that out of the six masks tested, the two molded mask models (3M 1860 and 8210) displayed significant functional failure after the first cycle but the other masks (all layered fabric, pleated), retained integrity throughout the 10 cycles tested (Kumar *et al.* 2020). More research should focus on autoclaving as this is a sterilization tool available to many WRRFs.

Moist heat

Moist heat is commonly used in health care but is not common at WRRFs. Investigating a lower range of temperatures for disinfection, STERIS produced a factsheet stating that their AMSCO® century medium steam sterilizers can achieve at least 3-log reductions in viral load in the presence of soil for 3M® models 1860, 1860S, and 1804. Low temperature treatment showed no adverse impacts when decontaminated for 10 cycles. However, this method is reliant on the use of FDA-approved pouches and changing cycle specification to an exposure phase temperature of 63–73 °C and pressure of 5–12 psi for 30 min (STERIS 2020). 3M supports the use of STERIS moist heat methods with high temperature self-sealing, FDA approached pouches for their 3M N95 masks models 1860, 8210, 1804, 1870+ (one FFR per pouch) at 65 ± 5 °C and 50–80% RH for 30 min (3M 2020). These temperature settings are not common on regular autoclaves, which operate at higher temperatures and are more likely to be found in health care settings that use wet pasteurization. Major parameter changes on equipment should be set up in collaboration with the equipment specialist, and testing inactivation using commercially available biological indicators to ensure the method is working would be advisable. Moist heat disinfection also requires the use of specialized pouches that are also in short supply during pandemics.

Simpler setups in laboratories may be possible. Liao *et al.* (2020) tested exposure to steam over a boiling beaker at approximately 125 °C for 10 min but found that after five cycles, N95 mask filtration performance was impacted (Liao *et al.* 2020). Wigginton *et al.* (2020) reported that an industrial washer drying cycle set at 80 °C with moderate relative humidity (62–66%) for 15 min achieved more than 3-log reductions in surrogates (Wigginton *et al.* 2020). This confirmed previous findings on the efficacy of moist heat treatments at 65 °C for 30 min (85% RH) for achieving more than 3-log reductions in influenza virus (Heimbuch *et al.* 2011). Repurposing a washer drying cycle would require involvement of the equipment representative or product specialist.

A team at Beijing University devised an at-home protocol for low-risk individuals that required steeping non-woven, used masks in hot water at 60–80 °C for 30 min and then drying the masks with a standard – but non-static – hair dryer for 10 min to regenerate charge. Successful regeneration is confirmed by sprinkling the mask with small scraps of paper that should stick. They suggested that masks and surgical masks could be decontaminated using this method without impacts on filtration capacity for one and 10 cycles respectively (Mackenzie 2020). We do not recommend the use of this technique since no mask fit-testing data is available.

Dry heat

Many of these studies rely on the use of commercially available microwaves (1,100 W), lab ovens or industrial drying systems; the first two are usually available at wastewater laboratories. Microwave-generated steam is of particular interest since it is affordable, equipment cost is minor and minimum training is required for operation. This method does present challenges when it comes to standardization of protocols, acquiring sterilization pouches (Zulauf *et al.* 2020) and melting the metal components of the mask that impact fit (Viscusi *et al.* 2009; 3M 2020). Any wastewater laboratory that runs total

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suspended solids on plant samples has access to an oven, also making it an attractive option.

Zulauf *et al.* (2020) packaged N95 respirators in glass containers with a mesh top in a 1,100 W commercially available microwave for 3 min. They reported an average of 5–6-log reductions in MS2 phage after a single treatment. They reported that mask performance was not impacted after 20 sequential cycles of microwave steam decontamination. Fischer *et al.* (2020) examined the use of an oven set at 70 °C for 60 min and found that 5-log reductions could be achieved. Acceptable fit could only be maintained for two rounds of decontamination. Liao *et al.* (2020) tested filtration capacity and pressure drop after exposing N95 masks to 85 °C at 0, 30 and 100% RH (flow rate 85 L/min) for 30 min. No significant changes in filter performance were detected for 20 rounds of decontamination and humidity had no impact on these results (Liao *et al.* 2020). They suggested that the use of dry heat at 75 °C for 30 min for 20 cycles may be promising. Wigginton *et al.* (2020), on the other hand, cautioned that viral inactivation is highly reliant on the presence of moisture and reported only 1–2-log reductions in surrogates when exposed to 80 °C for 15 min at 8% RH (Wigginton *et al.* 2020).

Other methods and consideration

Various authors cite that alcohol and bleach destroy the static charge of N95 masks and therefore cannot be used for disinfection (Mackenzie 2020). More recently this finding was confirmed by Fischer *et al.* (2020), who reported that N95 mask filtration efficacy drops significantly after the first round of decontamination with 70% ethanol. Similarly, Liao *et al.* (2020) found that immersing N95 masks in 75% ethanol and in 2% chlorine solution for 5 min results in both filtration efficiency and pressure drops, rendering the masks ineffective.

EtO, while efficacious against microorganisms, is flammable and a known carcinogen. It should not be used for disinfecting respiratory protective equipment due to risk of

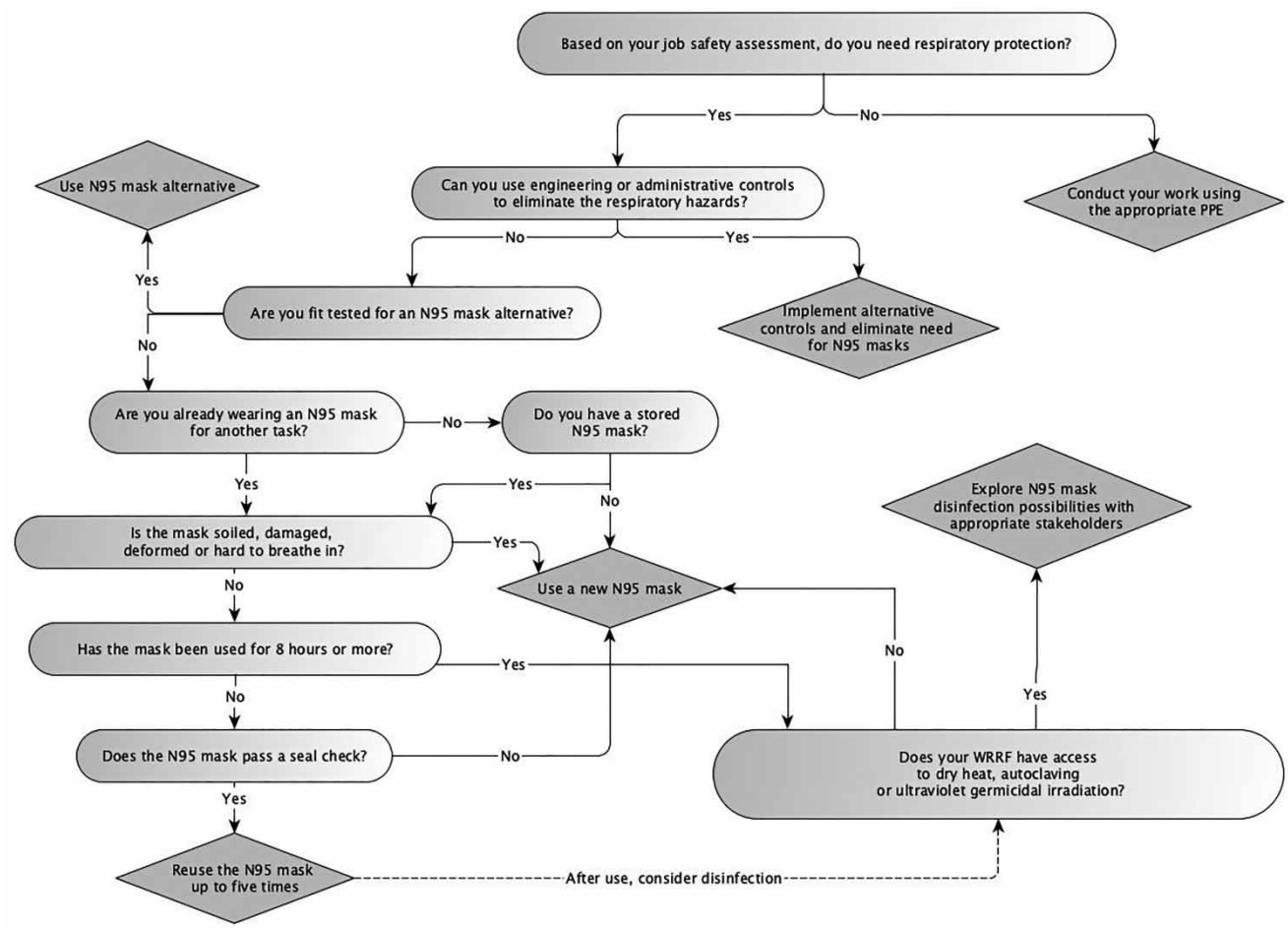

Figure 2 | Decision tree for N95 mask use at water resource recovery facilities.

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off-gassing (3M 2020). Wigginton *et al.* (2020) tested EtO sterilization using a 3M Steri-Vac 5XL EtO system. They reported achieving 5.8-log reductions in surrogates after 1 hour of exposure at 55 °C and 45% RH. They report that EtO was still not deemed safe after 12 hours of aeration (15-hour total cycle). Kumar *et al.* (2020) reported that EtO could be used for three cycles on N95 masks without significant structural or functional degeneration. They performed EtO gas treatment using the 5XLP Steri-Vac sterilizer/aerator (3M Company, St. Paul, Minnesota) with a 1-hour exposure and 12-hour aeration time. They did not test for off-gassing but proposed that this may be a plausible way to disinfect masks in resource-poor locations. We advise against their recommendation until the safety of the wearer is confirmed.

Finally, authors have highlighted the importance of having a full administrative system in place if reuse and disinfection are attempted. This includes a standardized and uniform N95 mask pick-up system in paper bags for sterilization, the designation of specific staff members to handle pickup, delivery and decontamination, a system to ensure soiled or damaged respirators are disposed of, an extensive quality assurance and quality control program, and a system to return N95 masks to their previous owners (Grossman *et al.* 2020; Lowe *et al.* 2020). These masks must be fit tested using OSHA-accepted fit-testing protocols after disinfection and prior to use to ensure worker safety.

CONCLUSIONS

As the numbers of COVID-19 cases continued to grow globally, severe shortages in PPE made it increasingly difficult for many WRRFs to procure respiratory protection for its employees and justify the need for respiratory protection in light of lacking standards. To prepare for future pandemics, strategic and holistic strategies to cope with PPE shortages must be developed, relying on strategies such as N95 mask use reduction, elimination and substitution, as well as reuse, extended use and disinfection. Figure 2 provides a decision tree that can be used at WRRFs to select the most appropriate N95 mask use strategy.

Studies that have investigated N95 mask disinfection strategies have looked at hydrogen peroxide, autoclaving, moist heat, dry heat, UVGI and other less suitable strategies (EtO, chlorine and ethanol). Of these studies, dry heat, autoclaving and UVGI are the most promising, but UVGI is likely only useful at large WRRF labs with biosafety cabinets. Unfortunately, none of these methods are approved by the US FDA and OSHA does not currently have any PPE standards for disinfecting N95 masks. More research needs to be conducted in this area, taking into consideration that WRRF laboratories do not have access to the same equipment as health care facilities.

We recommend that utility and wastewater laboratory managers work closely with disinfection technology manufacturers, mask providers, health and safety staff, auditors and inspectors from regulating bodies and laboratory managers to develop appropriate programs for disinfection and reuse of masks.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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