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Assessing and managing SARS-CoV-2 occupational health risk to workers handling residuals and biosolids

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HIGHLIGHTS

• There is no evidence linking WRRF residuals and infection risk from SARS-CoV-2.
• Quantification of SARS-CoV-2 in wastewater is not indicative of infectivity.
• Workers should continue to follow industry safety practices to minimize risk.
• Additional studies are merited on environmental persistence and risk modeling.

ABSTRACT

Current wastewater worker guidance from the United States Environmental Protection Agency (USEPA) aligns with the Centers for Disease Control and Prevention (CDC) and the Occupational Safety and Health Administration (OSHA) recommendations and states that no additional specific protections against SARS-CoV-2, the virus that causes COVID-19 infections, are recommended for employees involved in wastewater management operations with residuals, sludge, and biosolids at water resource recovery facilities. The USEPA guidance references a document from 2002 that summarizes practices required for protection of workers handling class B biosolids to minimize exposure to pathogens including viruses. While there is no documented evidence that residuals or biosolids of any treatment level contain infectious SARS-CoV-2 or are a source of transmission of this current pandemic strain of coronavirus, this review summarizes and examines whether the provided federal guidance is sufficient to protect workers in view of currently available data on SARS-CoV-2 persistence and transmission. No currently available epidemiological data establishes a direct link between wastewater sludge or biosolids...
and risk of infection from the SARS-CoV-2. Despite shedding of the RNA of the virus in feces, there is no evidence supporting the presence or transmission of infectious SARS-CoV-2 through the wastewater system or in biosolids. In addition, this review presents previous epidemiologic data related to other non-enveloped viruses. Overall, the risk for exposure to SARS-CoV-2, or any pathogen, decreases with increasing treatment measures. As a result, the highest risk of exposure is related to spreading and handling untreated feces or stool, followed by untreated municipal sludge, the class B biosolids, while lowest risk is associated with spreading or handling Class A biosolids. This review reinforces federal recommendations and the importance of vigilance in applying occupational risk mitigation measures to protect public and occupational health.

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1. Introduction

The treatment of wastewater at Water Resource Recovery Facilities (WRRFs) often requires the separation of the liquid from the solids portion of the influent during primary and secondary clarification. Depending on the level of treatment at the facility, these solids or residuals are called sludge or biosolids, and can be used to improve soil health, recycle nutrients, and reduce fertilizer use in agriculture, forestry and land reclamation globally (Canadian Council of Ministers of the Environment, 2012 (Canadian Council, C, 2015). Treatment, reuse and recycling of wastewater sludge require the involvement of a wide range of workers, such as producers, transporters, applicators and farmers (Australian and New Zealand Biosolids Partnership, 2020).

While health, safety and hygiene recommendations are in place to protect these workers, the majority of recommendations in North America are more than a decade old (Burton and Trout, 1999). Utilities often inquire if workers handling wastewater, residuals and biosolids are at risk and whether these standards need to be updated.

Wastewater worker safety concerns have been amplified by the current COVID-19 pandemic and the contradictory risk mitigation recommendations in the quickly growing SARS-CoV-2 literature. Various authors and organizations have concluded based on current evidence that the occupational risk of infection with SARS-CoV-2 through wastewater exposure should be low given the unlikely infectious virus presence, as well as proper personal protective equipment (PPE) use and compliance with applicable regulatory treatment standards (Jones et al., 2012; Maal-Bared et al., 2020; Centers for Disease Control, 2020; OSHA, 2020; WHO, 2020). However, others have cautioned that application of sludge and biosolids during the COVID-19 pandemic carries significant risk (Langone et al., 2021; Patel et al., 2020). Reviews have recommended that sludge produced in cities with high numbers of cases should be incinerated or sent to the landfill (Liu et al., 2020b). Some health authorities, such as the Italian National Institute of Health, have issued precautionary sludge handling guidelines, which detail minimum retention times requires for sludge in relation to ambient temperatures (Collivignarelli et al., 2020). A recent quantitative microbial risk assessment by Dada and Gyawali (2020) suggested that risk of wastewater workers is only negligible when less than 0.3% of the population served by the plant is actively infected. Utilities, especially in smaller communities, neither have the resources nor the time to evaluate this emerging data.

Given these contradictions in risk evaluations related to solids handling, the highly variable and inconsistent concentrations of SARS-CoV-2 genetic material (RNA) recovered from feces and sewage, the paucity of reports of viable SARS-CoV-2 in feces and the heightened risk perception among workers in the water sector, a critical and peer-reviewed synthesis of current data available would support risk mitigation and communication for utilities and their workers. The present work highlights the most recent relevant publications, pre-prints and reviews that help determine whether additional risk mitigation measures are needed when workers handle wastewater treatment residuals. We will specifically focus on risk resulting from fecal-oral, bioaerosols and fomite exposures.

2. US EPA biosolids classification and regulations

Residuals are categorized into: (1) human feces, (2) untreated municipal sludge, (3) Class B biosolids and (4) Class A biosolids. As required by the Clean Water Act Amendments of 1987, in 1993 the United States Environmental Protection Agency (USEPA) developed the USEPA 40 Code of Federal Regulations Part 503 to protect public and environmental health from any potential negative effects that might be related to the application of sludge and biosolids to land (Reimers et al., 2004; USEPA, 1992; USEPA, 2018). The Regulation covered chemical pollutant limits, operational standards designed to reduce pathogens and attraction of disease vectors, as well as management practices.

US EPA defines Class A disinfected biosolids as those where pathogenic organism densities are reduced to below detectable limits which include Salmonella sp. to less than 3 Most Probable Number (MPN) per 4 g total solids, Enteric viruses to less than 1 Plaque Forming Unit (PFU) per 4 g total solids and viable helminth ova to less than 1 viable helminth ova/4 g total solids. Class A biosolids are achieved through a Process to Further Reduce Pathogens (PFRP). Class B biosolids can be achieved by showing that the sludge was treated by a Process to
Significantly Reduce Pathogens (PSRP) or that the treated biosolids contain less than 2 million Colony Forming Units (CFU) or MPN of fecal (thermotolerant) coliform bacteria per gram of biosolids (dry weight basis). While pathogens are greatly reduced in Class B biosolids, they are not completely eliminated, therefore there are public access, agricultural and grazing restrictions placed on their use in land application (USEPA, 1992).

In some circumstances, WRRF seek to incorporate a novel process for biosolids treatment that was not previously included in the original legislation. For a process to achieve an equivalency status, it must be approved by the USEPA’s Pathogen Equivalency Committee (PEC) (Fitzmorris et al., 2007). Table 1 broadly shows USEPA’s requirements for demonstrating equivalency of an innovative or alternative technology to a PSRP or PFRP equivalent process. The PEC has a strict protocol for this evaluation that includes describing the exact mechanism of disinfection along with key process control parameters. To demonstrate the required log reductions, the untreated sludge must contain an adequate number of organisms. For example, to demonstrate PFRP equivalency untreated sludge must contain more than 1000 PFU of enteric viruses /4 g TS (dry weight basis); and 100 viable Ascaris spp. ova/4 g TS. If the untreated sludge does not naturally contain these density levels, the applicant must spike the sample to demonstrate the process’ capability for achieving a 3-log reduction in enteric viruses and a 2-log reduction in viable Ascaris spp. Ova (USEPA, 2020; USEPA, 1992).

In addition, regulations governing residuals have been monitored and assessed by the National Academies of Sciences National Research Council (NRC, 1996; NRC, 2002). These reports evaluate the technical methods and approaches used by US EPA, focusing specifically on human health protection through risk-assessments and advances in the scientific database since promulgation of the regulation. The reports make recommendations for addressing public health concerns, uncertainties, and data gaps about the technical basis of the biosolids standards.

3. Biosolids disinfection processes: evaluation of effectiveness

Based on the available literature, virus densities vary greatly among specific pathogens and by residual category and the process used for pathogen removal (see Table 2). SARS-CoV-2 is an enveloped virus that differs from non-enveloped viruses due to the presence of the additional lipid membrane surrounding its capsid, where protein spikes and functional groups are located in an outer lipid membrane (Kumar et al., 2020). This structure results in both increased susceptibility to disinfection and environmental stressors CDC, 2008; Gattie and Lewis, 2004; Chin et al., 2020), as well increased partitioning into solids due to surface charge and relative hydrophobicity (Kumar et al., 2020). Thus, we would expect that no additional protective equipment or other prevention and control measures in response to SARS-CoV-2 are required for managing properly treated biosolids than those previously described and encouraged. Overall, the risk of exposure to SARS-CoV-2, or any pathogen, decreases with increasing fecal waste and biosolids treatment with the highest risk being associated with spreading untreated feces (stool) or other fecal wastes, followed by untreated municipal sludge, the class B biosolids, while lowest risk is associated with spreading Class A biosolids.

To assess potential risks resulting from SARS-CoV-2 exposure, reviews have relied primarily on data from viral indicator organisms (e.g., bacteriophages in Martin-Diaz et al., 2020 and Pillai et al., 2011), for coronaviruses other than SARS-CoV-2 and more recently SARS-CoV-2 RNA. Martin-Diaz et al. (2020) concluded somatic bacteriophages have potential as surrogates for pathogenic viruses in solid and semisolid fecal waste matrices due to their higher natural persistence and resistance to typical treatment mechanisms (Martin-Diaz et al., 2020). As viruses are typically adsorbed to solid particles both under natural and anthropogenic conditions, certain solids (Fongaro et al., 2017; Hurst et al., 1980; Sobsey et al., 1980; Feachem et al., 1980; Pederson, 1981) and water quality characteristics can affect the adsorption efficiencies of viruses to various matrices. These characteristics include pH, virus ionic characteristics (surface charge), virus surface hydrophobicity, dissolved salts, and organic matter among others (Hurst et al., 1980; Zhao et al., 2008; Bitton and Mitchell, 1974; Bixby and O’Brien, 1979). It has also been noted that other enveloped viruses used as SARS-CoV-2 surrogates (e.g. murine hepatitis virus (MHV) and Pseudomonas phage 66) exhibit higher partitioning to solids compared to non-enveloped viruses (Ye et al., 2016). Similarly, SARS-CoV-2 RNA has been documented in wastewater, primary sludge and waste activated sludge and is now being used as part of epidemiological and public health response efforts to track disease spread and prevalence in communities (Ahmed et al., 2020; Kocamenci et al., 2020; Pecchia et al., 2020; Balboa et al., 2020; D’Aoust et al., 2021); however, infectious virus has not yet been identified in wastewater or biosolids. Additional review of the current state of knowledge related to coronavirus detection, presence and persistence in the water and wastewater environment may be found in the available literature (Carducci et al., 2020; Jones et al., 2020; Patel et al., 2020; Collivignarelli et al., 2020; Elsamadony et al., 2021; Maal-Bared et al., 2020; Foladori et al., 2020; Katakis et al., 2021).

Coronaviruses die off rapidly in wastewater compared with waterborne enteroviruses, with the time required for the virus amounts to decrease 99.9% between 2 and 4 days before any treatment at 23 °C (Gundy et al., 2009; Bivins et al., 2020). Even in the examination of non-enveloped, enteric viruses, the typical multi-barrier wastewater treatment approach, which may include primary sedimentation and coagulation, trickling filters or activated sludge, disinfection and membrane filtration, have been shown to achieve a greater than 99.9% reduction in viral load (Pepper et al., 2006). Heat treatment of wastewater amended with SARS-CoV-2 rapidly inactivated infectious virus (Bivins et al., 2020).

Mesophilic anaerobic digestion reduced enteric virus (believed to be largely enteroviruses) numbers in digested sludge by an average of 94.4% (1.97 log10), while thermophilic anaerobic digestion reduced enteric viruses by 4.6 to 7.1 log10, or to below detection limits (>2.8 to >5.8 log10), depending on the virus (Sassi et al., 2018). Wang et al. (2005) noted SARS-CoV-1 virus was more susceptible to disinfectants (free chlorine more effective than chlorine dioxide) than E. coli and phage. Table 3 highlights the ranges in log reductions by sludge treatment type (Godfree, 2003; Ward, 1984).

Recently, Chin et al. (2020) confirmed SARS-CoV-2 sensitivity to heat and disinfectants. While coronaviruses have been shown to survive up to 9 days on surfaces, inactivation can be achieved with 62% to 71% ethanol, 0.5% hydrogen peroxide, or 0.1% sodium hypochlorite within 1 min with higher temperatures also reducing survival (40 °C as compared to 20 °C) (Kampf et al., 2020; Fathizadeh et al., 2020). The results from this meta-analysis correspond with recent SARS-CoV-2 research by Chin et al. (2020) that reported the inability to recover any infectious virus (>7.8 log10 reduction) from viral transport medium after 5-min incubation at 22 °C with various disinfectants with the exception of soap and water (4.2 log10 reduction). The latter study also reported that SARS-CoV-2 is extremely stable in a pH range of 3–10 at room
temperature (Chin et al., 2020). Thus, disinfection of contaminated surfaces and personal hygiene measures (e.g., hand hygiene) are documented to be effective and therefore critical to mitigate risk of infection by SARS-CoV-2 and other pathogens (Heneghan et al., 2020).

Most virus-related research in the biosolids field has been on enteroviruses. Work by Gundy et al. (2009) showed that SARS-CoV-1, a relative of the SARS-CoV-2, displays less environmental persistence in primary and secondary effluent compared to poliovirus (an enterovirus), which is used as an indicator for biosolids PFRP equivalency. Wang et al. (2005) noted SARS-CoV-1 virus was more susceptible to disinfectants than E. coli and f2 phage, with free chlorine more effective than chlorine dioxide. Recent work has observed that scavenger and bacteriophages could be suitable surrogate indicators for viruses due to the similarity of their resistance to treatment (Diaz et al., 2020; Viau and Peccia, 2009; Gerba et al., 2018; Casanova and Weaver, 2015). It should be emphasized that existing and proposed non-enveloped virus surrogate viruses are expected to display higher levels of resistance to environmental stressors and disinfection compared to enveloped viruses in general and SARS-CoV-2 specifically, thereby making them conservative indicators (Centers for Disease Control (CDC), 2002).

4. Presence of SARS-CoV-2 in each class of residuals and likelihood of transmission

4.1. Qualitative risk based on virus persistence and routes of transmission

Determining the risks for pathogens such as SARS-CoV-2 must consider their occurrence, persistence, routes of transmission and dose-related probabilities of infection and illness, among other properties. This is best done using quantitative microbial risk assessment (QMRA), which typically includes five stages: a) hazard identification; b) exposure assessment; c) dose–response assessment, d) risk characterization and e) risk management. As quantitative infectivity dose-response parameters of SARS-CoV-2 remain unknown at the time of this publication, performing a formal quantitative microbial risk assessment is not possible. However, a qualitative risk assessment can be performed based on an analysis of the hazards identified. This approach includes consideration of the presence and potential infectivity of SARS-CoV-2 in the four categories of residuals along with their likelihood of transmission to workers through various exposure routes. The most relevant transmission routes that should be considered to mitigate risk of occupational infection with SARS-CoV-2 for workers handling residuals and biosolids are the fecal oral route, bioaerosols, fomite transmission and direct personal contact. Overall, magnitude of risk resulting from exposure to a fecal solids residual category is higher the less treatment the residual receives prior to handling and spreading or other final disposition (e.g., landfill or incineration). The highest risk would be related to spreading or otherwise having intimate contact with feces or stool, followed by untreated municipal sludge, the class B biosolids, while lowest risk would be related to spreading or otherwise handling Class A biosolids.

4.1.1. Human feces/stool

Prior to the emergence of SARS-CoV-2, a focus of concern about feces-associated coronaviruses was with SARS-CoV-1 and some of the respiratory coronaviruses causing the common cold. The presence of SARS-CoV-1 RNA in stool samples was reported initially by He et al. (2004) in 57.4% of SARS patients; this study utilized fluorescence-based quantitative polymerase chain reaction or FQ-PCR method which does not determine infectivity. Additional quantification of the median duration of SARS-CoV-1 virus RNA excretion from stools was 27 days (16 to 126 day range), but no infectivity was reported (Liu et al., 2004; Hung et al., 2004).

Studies on other coronaviruses, namely SARS-CoV-1 indicated the virus survived in in-vitro experiments in feces only 3 days at 20 °C, but at 4 °C persisted for 17 days (Wang et al., 2005). Detection frequencies of the genetic material (RNA) of other coronaviruses in feces of infected individuals ranged from 16% to 97% with a peak for SARS-CoV-1 RNA at 9 to 14 days after illness onset (Cheng et al., 2004; Wigginton et al., 2015; Wigginton and Boehm, 2020). Three other human coronaviruses — HCoVNL63, HCoV-OC43, and HCoV-229E — that infect the upper respiratory tract have been detected in stool samples (Esper et al., 2010; Risku et al., 2010).

In the case of SARS-CoV-2, a meta-analysis conducted by Jones et al. (2020) concluded that 11% of COVID-19 patients experience diarrhea. Studies specifically examining the presence of SARS-CoV-2 RNA in stool samples from laboratory-confirmed positive patients report detection in 29–64% of patients (Wu et al., 2020; Chen et al., 2020; Holshue

| Source | Comments relevant to virus removal | Average number of viruses/g matrix | References |
|--------|-----------------------------------|-----------------------------------|------------|
| Raw human feces (Feachem et al., 1980; Shuval and Fattal, 2003; Metcalf and Eddy et al., 2014) | It can be called Night Soil, Septage or Human Feces; without treatment, the infectivity of most viruses present in feces decreases by half within the range of 7 days to 6 months (Reimers et al., 2001; Madeley, 1979) | Enteroviruses: 10^4–10^7 Hep A virus: 10^8 SARS: 10^8.5 Coliphages: 10^8–10^9 Enteroviruses: 10^2–10^3 Noroviruses: 10^3–10^7 | Shuval and Fattal (2003) Shuval and Fattal (2003) Hung et al. (2004) |
| Raw Municipal Sludge Pederson (1981) | WRFR report identified over 250 viruses (Pilla et al., 2011). Infectivity ranged from 2 days to 6 months Reimers et al. (2001), | Coliphages: 10^2–10^6 Enteroviruses: 10^2–10^6 Enteroviruses: 10^2–10^6 | Metcalf and Eddy et al. (2014); Yates and Yates (2007) Shuval and Fattal (2003); Reimers et al. (2001) Gerba et al. (2011) Yates and Yates (2007) Shuval and Fattal (2003) |
| Class B Disinfected Biosolids (PSRP) USEPA (1992) | Viruses found in partially disinfected biosolids will inactivate once applied to soil in outdoor field conditions between 30 days and 3 months | | |
| Class A Disinfected Biosolids (PFRP) USEPA (1992) | Class A processes are required to obtain virus reduction of <1 PFU/g dry weight solids. | | Reimers et al. (2001) |

Table 2
Summary of virus levels in human waste residuals.

| Treatment | Log_{10} reduction range | Bacteria | Viruses | Parasites |
|-----------|--------------------------|----------|---------|-----------|
| Mesophilic anaerobic digestion | 0.5 to 4 | 0.5 to 2 | 0 |
| Aerobic digestion | 0.5 to 4 | 0.5 to 2 | 0 |
| Composting | 2 to >4 | 2 to >4 | 2 to >4 |
| Air drying | 0.5 to 4 | 0.5 to >4 | 0.5 to >4 |
| Lime stabilization | 2 to >4 | >4 | 0 |
et al., 2020; Xiao et al., 2020a, 2020b; Ong et al., 2020; Tang et al., 2020; Wölfel et al., 2020). Similarly, the prolonged shedding of SARS-CoV-2 RNA in feces by COVID-19 patients has been reviewed in the literature (Jefferson et al., 2020; Foladori et al., 2020). Wölfel et al. (2020) reported that stool samples remained RNA-positive over 3 weeks in six of the nine examined patients, in spite of full resolution of symptoms.

Recent work has shown that SARS-CoV-2 binds to the angiotensin-converting enzyme 2 (ACE2) receptors on Type II alveolar cells and intestinal epithelia (Hoffmann et al., 2020; Wan et al., 2020; Wrapp et al., 2020). Its ability to attach to these cell receptors in the intestinal tract supports the potential for fecal–oral transmission if the virus survives in the gut to then be fecally excreted. Details regarding infectivity of the SARS-CoV-2 may be found in the following references and also detailed in the WIDOC recommendations (Dhama et al., 2020; Maal-Bared et al., 2020; Prusin et al., 2020; Rodríguez-Lázaro et al., 2012; Lamers et al., 2020). It is noteworthy that since the onset of the outbreak in December 2019, only seven studies have reported the presence of infective (replication-capable) SARS-CoV-2 in feces at the time of submission of this article (Zhang et al., 2020a; Wang et al., 2020; Xiao et al., 2020a; Xiao et al., 2020b; Jeong et al., 2020; Kim et al., 2020; Yao et al., 2020). Xiao et al. (2020a) reported concentrations of viable virus based on infectivity in mammalian cell cultures, and Xiao et al. (2020b) found evidence of viable virus in gastrointestinal endoscopic specimens by specific immunofluorescence in intestinal tissue cells and electron microscopy. Other studies detected virus infectivity by experimental infection of ferrets with stool supernatant (Jeong et al., 2020; Kim et al., 2020), and visual observation of virus replication and growth in tissue by electron microscopy. Jeong et al. (2020) was unable to detect SARS-CoV-2 in VERO cells but the culture negative fecal samples were used to successfully infect ferrets with SARS-CoV-2, bringing into question the efficacy of some of the current cell culturing methods.

There is evidence that antiviral agents in the lower intestine rapidly inactivate most of the infectious virus that may be present from replication in the small intestine (Zang et al., 2020). Recent laboratory and clinical study documents that new viruses released into the intestinal lumen are rapidly inactivated by human colonic (gut) fluids, resulting in no infectious virus recoverable from the stool specimens of COVID-19 patients (Zang et al., 2020). Further consideration of these studies along with an overview of the impact of SARS-CoV-2 on WRRF and the water industry in general is summarized by various authors (Carducci et al., 2020; Jones et al., 2020; Patel et al., 2020; Collivignarelli et al., 2020; Elsamadony et al., 2021; Maal-Bared et al., 2020; Foladori et al., 2020; Katali et al., 2021).

It is noteworthy that there is currently little epidemiological or virological evidence that SARS-CoV-2 is transmitted by the fecal–oral route. A documented incident occurred for the SARS-1 coronavirus in Hong Kong in the Amoy Gardens complex, where possible evidence of airborne transmission due to faulty wastewater piping in a building (Brown, 2020). Both the World Health Organization (WHO) and further studies have indicated airborne transmission of viruses was likely but did not present conclusive evidence linking the airborne transmission to feces (WHO, 2003; Yu et al., 2014; Yu et al., 2004). A recent report suggests that SARS-CoV-2 in airborne human wastewater may have caused 9 COVID-19 in cases among 3 families in a high-rise apartment building in a Chinese city (Kang et al., 2020). The 3 families lived in 3 vertically aligned flats connected by drainage pipes in their master bathrooms. The observed infections, the locations of SARS-CoV-2 RNA-positive environmental samples from bathroom surfaces, subsequent aerosol studies and aerodynamic modeling were considered consistent with vertical spread of virus-laden wastewater aerosols via stacks and vents.

Based on the limited number of studies that were able to culture viable SARS-CoV-2 from fresh feces and the lack of infective virus detections in wastewater, it is reasonable to assume that the highest risk of infection would be related to exposure to freshly excreted feces in the bathroom, plumbing system, and the collections system (Gormley et al., 2020; Jones et al., 2020) and in conditions where recommended hygiene and sanitation practices are difficult to apply (Lodder and de Roda Husman, 2020; Jones et al., 2020; Kumar et al., 2020; Liu et al., 2020b).

Studies have confirmed similarities in survival of the SARS-CoV-2 and SARS-CoV-1 on surfaces and in aerosols (median half-life 1.1 to 1.2 h and 95% confidence intervals of 0.64 to 2.64 for SARS-CoV-2 and 0.78 to 2.43 for SARS-CoV-1) (van Doremalen et al., 2020). These factors are important when considering both likelihood of transmission and appropriate surrogate organisms for examining comparative studies involving different categories of residuals spanning a range of treatments. Evidence related to the role of bioaerosols in transmission of SARS-CoV-2 remains controversial. It is important to recognize that this may be related to the difficulty in sampling and characterizing the infectivity of airborne viruses (Morawska and Cao, 2020), which is highly dependent on the virus type, environmental conditions, and on the methods of collection and handling of bioaerosol samples (Cao et al., 2011). van Doremalen et al. (2020) confirmed SARS-CoV-2 survival for more than 3 h in experimentally generated aerosols under laboratory conditions. The team concluded that the half-lives of SARS-CoV-2 and SARS-CoV-1 in air were comparable at 1.1 to 1.2 h under the conditions tested. More recently, Fears et al. (2020) supported these findings confirming that in laboratory conditions infectious SARS-CoV-2 was detected at all time points during the aerosol suspension stability experiment for up to 16 h. Kim et al. (2020) reported that ferrets were indirectly infected with SARS-CoV-2 in an experimental set up. The authors suggested this may support bioaerosols transmission. Meanwhile, other studies reported the inability to recover SARS-CoV-2 RNA from patients’ rooms (Ong et al., 2020) and a public space (Cai et al., 2020), or the recovery of low concentrations of SARS-CoV-2 RNA from patient room air samples (Liu et al., 2020a). Only one study to date has reported the detection of infectious SARS-CoV-2 in the air of ill patients’ rooms when the air sampler was at the foot of their beds. Infectious virus concentrations were present in only some samples and were very low compared to concentrations of viral RNA (by about 100-fold) (Santarpia et al., 2020).

4.1.2. Untreated municipal sludge

From the Netherlands, Australia, France, the U.S. and a growing number of countries, SARS-CoV-2 genetic material (nucleic acid) but not infectious virus has been found in municipal wastewater (Medema et al., 2020; Ahmed et al., 2020; Wu et al., 2020). It is important to note the identification of infectious virus was not the goal of the referenced studies. Medema et al. (2020) reported the occurrence of SARS-CoV-2 RNA in municipal wastewater before cases were identified in the population. Detection of SARS-CoV-2 RNA in wastewater has now become a supplemental tool for early detection and tracking of COVID-19 infections in populations and has been used to support rapid public health response to prevent outbreaks (Polo et al., 2020; Betancourt et al., 2020). Previous studies also have also reported SARS-CoV-1 (Bibby and Peccia, 2013) and now SARS-CoV-2 RNA in untreated wastewater sludge and Class B biosolids as recent efforts to also monitor SARS-CoV-2 RNA in WRRF sludge (Balboa et al., 2020; D’Aoust et al., 2021). Again, these assessments were performed by nucleic acid (genetic) analysis and do not indicate infectivity of the virus genetic material detected.

4.1.3. Class B (PSRP) biosolids

While enveloped viruses, such as coronaviruses are expected to be susceptible to disinfection and environmental stressors, the shedding of SARS-CoV-2 in various bodily secretions that are commonly released into the collection system in domestic wastewater have been reported, based on detecting virus RNA (To et al., 2020; Peng et al., 2020; Zhang et al., 2020a,b). These reports, along with the detection of high concentrations of SARS-CoV-2 RNA in wastewater, imply the potential
presence of infective virus in untreated wastewater. So far, such presence of infectious in wastewater or biosolids has not been documented. Studies have reported that SARS-CoV-2 RNA has not been detected by molecular methods when analyzed in treated effluent (Rimoldi et al., 2020). Thus, based on previous research on SARS-CoV-2 and other coronaviruses, the likelihood that Class B biosolids will contain infective SARS-CoV-2 seems low (Wolff et al., 2005) but remains unknown until the presence of infectious virus in such samples is documented experimentally and traditional Quantitative Microbial Risk Assessments can be conducted. However, concentrations in Class B biosolids of enteric viruses, which are more resistant to treatment than SARS-CoV-2, after mesophilic anaerobic digestion have been reported to range between $10^5$ and $10^6$ MPN/g (Wong et al., 2010), which emphasizes the need for worker infection prevention and control, including PPE.

Potential risk from pathogenic microorganisms associated with land application of biosolids varies based on the biosolids application method, the microbiological quality of the biosolids at the time of application, environmental factors, and the management of the application site (Yates and Yates, 2007). While the quantitative dose-response relationship for SARS-CoV-2 is currently unknown, prior risk assessment models of bioaerosol transport indicate little risk to surrounding communities and workers at application sites. In fact, negligible risk was determined from aerosolized Coxsackievirus (an enterovirus) at estimated distances of 10,000 m from the site and a 3% risk was estimated to workers on site (2 m/s wind, 1 h of exposure) (Dowd et al., 2000). It is also of note that these models tend to overestimate actual risk to populations by the nature of their design. From the limited evidence of viruses found in aerosols, even with variations in application methods, there is no indication of enteric viruses found further than 5 m from biosolids application areas (Brooks et al., 2004).

Westrell et al. (2004) reported the application of hazard analysis and critical control points along with quantitative microbial risk assessment tools to quantify risk to workers and communities surrounding land application sites (Class B, mesophilic anaerobically digested biosolids). They found the highest individual risk from a single exposure occurred via aerosols for workers at the belt press for dewatering (prior to Class B treatment) and overall risk was highest in the early processes, prior to exposures to stressors and use of disinfection as opposed to during land application (Westrell et al., 2004).

Class B biosolids are not likely a significant source of transmission for SARS-CoV-2 based on current evidence. Over the last 40 years, there have not been recorded infections due to viruses in Class B biosolids applications as noted by the National Research Council reports (NRC, 1996 & NRC, 2002). Therefore, no supplementary measures are needed for protecting workers against SARS-CoV-2 beyond what is typically used when handling Class B biosolids. See CDC (2002) recommendations for additional details on these measures.

4.1.4. Class A (PFRP) biosolids

It is of note that the vast majority of research related to virus presence and survival in biosolids, including research on the effectiveness of treatment, has been focused on non-enveloped viruses. As previously stated, non-enveloped viruses, such as polioviruses, other enteroviruses, adenoviruses and reoviruses are much more robust than enveloped viruses, such as the SARS-CoV-2. One study on these non-enveloped, primarily enteric viruses showed thermophilic digestion to be more effective than mesophilic anaerobic digestion (Wong et al., 2010). Mesophilic anaerobically digested Class B biosolids further treated to Class A with heat pelletization (35° to 37 °C for 10 to 20 days, dewatering, followed by a low-pressure oxidation drying system) and composting (agitator windrow method) resulted in even lower virus levels (Viuia and Peccia, 2009). Therefore, evidence documents that the risks of contracting COVID-19 from Class A biosolids are negligible. The virus itself is less stable than the enteric virus surrogate utilized to get approval as disinfected Class A biosolids by the USEPA PEC (Wang et al., 2005).

5. Prevention and control

Current prevention and control practices regarding the appropriate use of PPE when in potential contact with untreated wastewater and municipal sludge are considered to be effective, even in the vicinity of processes that create airborne droplets and aerosols. In general, agencies should follow recommendations from the U.S. Occupational Safety and Health Administration (OSHA) (2020) and local occupational health and safety agencies based on the conditions at their local facilities. Similar recommendations have also been developed by the World Health Organization (WHO, 2020) and the European Union (EU) (European Centre for Disease Control, 2020).

5.1. Recommendations for worker protection

In alignment with CDC (2002), WHO (2020), EU (European Centre for Disease Prevention and Control, 2020) and OSHA (2020) recommendations, we recommend that workers and employers manage untreated residuals and sludge with potential or known SARS-CoV-2 contamination like any other untreated material. As noted by LeChevallier et al. (LeChevallier et al., 2020) there is a hierarchy of PPE and other prevention and control measures that follows the treatment through the WRRF. As material progresses through treatment, risk decreases. Contact transfer prevention PPE including gloves, boots, and uniform/coveralls should be utilized throughout WRRF operations, with the addition of safety glasses/goggles or face shields in areas with splash hazards. Overall, the use of typical engineering and administrative controls, safe work practices, and PPE when handling untreated wastewater, feces, and untreated municipal sludge to prevent worker exposure is important and considered necessary.

In general, agencies should follow recommendations from OSHA (2020) and the state agency responsible for occupational health and safety in the USA and those of other worker health protection authorities in other countries. More specifically, the following recommendations should be highlighted during this time (Burton and Trout, 1999):

1. As is current practice, remain mindful of the operation; take precautions to minimize the production of droplets and aerosols from feces and municipal sludge in the collections system and in the headworks of the WRRF. In addition, when land applying Class B biosolids, observe site buffer requirements as outlined in permits.

   ○ Management notes: Periodic training regarding standard hygiene practices and PPE use and maintenance should continue. Ensure workers are up to date on CDC-recommended and World Health Organization vaccinations such as tetanus–diphtheria and hepatitis A immunizations.

2. Wash hands often, carry disinfecting wipes and disinfecting gel to use anytime the operator touches surfaces that may have been exposed to liquids, droplets or aerosols. Switches, valves, and other surfaces exposed to aerosol from processes prior to complete biosolids treatment should be sanitized. Operators also should sanitize exposed surfaces prior to leaving an area to assure surfaces are as sanitary as possible and do not pose a hazard to other personnel.

   ○ Management notes: Hand-washing stations with clean water and mild soap should be readily available wherever contact with wastewater or sludge may occur.

3. During operation, wear heavy rubber gloves over surgical gloves as well as goggles or face shield. If surgical gloves are used, discard them and sanitize the outer rubber gloves.

   ○ Management notes: CDC has established guidelines for workers along with WHO and the EU.

4. At the end of a shift at the office or maintenance shop, change out field clothes, place in clothes hamper for dirty clothes/uniforms/...
shower, and change into street clothes before heading home. If you go directly from the field to home, take steps to protect family members. Specifically, remove clothes in mudroom, garage, or laundry room. Handle as dirty clothes and do not commingle dirty clothes from the household with field clothes. Remove field boots before entering home and wash boots (especially the bottoms) before entering house, office, or personal vehicle.

In summary, be aware of hazards. Wash hands frequently and especially before smoking, before drinking water or other beverages, before eating and applying cosmetics. Avoid hand contact with face and do not touch face with glove covered hands. Face coverings can help with protecting face from contact with gloves.

6. Conclusions

Based on the evidence presented, there is no currently available epidemiological data that establishes a direct link between wastewater sludge or biosolids and risk of infection from the SARS-CoV-2. Despite shedding of the virus RNA in feces, there is no evidence supporting the transmission of SARS-CoV-2 through the wastewater system including biosolids. Research efforts have been undertaken to quantify the presence of the virus in wastewater, but infectivity analyses for viable, replication-competent virus has thus far not been included in most studies and has not been reported to date. There may be a lack for the basis of the lack of virus infection presence, including their inactivation by fluid contents in the gut (the colon) (Zang et al., 2020) and the generally lower survival of enveloped viruses than non-enveloped viruses in environmental matrices, as the paper points out clearly in the Fig. 1. Put simply, while the presence of RNA in wastewater has been widely detected, it does not indicate the virus is infective and poses a health risk.

Attempts to quantify the risks from these virus in wastewater and biosolids are hampered by the lack of evidence for infectious virus in wastewater or biosolids and also the lack of any quantitative data on infectivity dose–response for this virus. So, any formal risk assessment would be based on huge assumptions for these variables that are probably not scientifically justifiable. Therefore, we are left with the need to estimate risk based on other sources of data, such as epidemiological data which indicates to date that this is not a virus for which fecal transmission is possible. Environ. Sci. Technol. Lett. 2, 76-84 (2015). https://doi.org/10.1021/acs.estlett.0c00730.

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Fig. 1. Pathogenic microorganisms present in wastewater sludge by pathogen class and their susceptibility to disinfection and environmental stress. (CDC, 2008; Gattie and Lewis, 2004; Image: CDC Public Health Image Library https://phil.cdc.gov/Default.aspx).
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