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Unprecedented environmental and energy impacts and challenges of COVID-19 pandemic

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\textbf{ABSTRACT}

The rapid transmission tendency, severity, and wide geographical spread of newly emerged novel coronavirus (SARS-CoV-2) in different environmental matrices, including water, air, and soil, has posed severe health, environmental, energy, and economic challenges worldwide. Despite the severe health effects, unprecedented improvements in air quality in many countries due to emergency measures, and public behavior changes have been reported. SARS-CoV-2 has been detected in air and sewage samples in several studies across the globe. The use of wastewater-based epidemiology (WBE) could be a valuable method to monitor the outbreak of COVID-19, which requires fast and reliable methods for virus detection in sewage. However, water treatment companies face many pressures due to potential for aerosolization, PPE shortages, and changed usage patterns. In addition, the unprecedented impact of the COVID-19 outbreak on the worldwide economy especially the energy sector, and its impact on our ecosystem required instant responses. This article discusses the recent developments and challenges faced in water, air, and energy resources, including renewables and non-renewables as the significant and interrelated components of the ecosystem. Furthermore, some recommendations have been directed, which may serve as a guideline to the scientists, legislators, and other stakeholders. A future roadmap has been proposed to overcome the tragic effects of COVID-19 and developing a sustainable environmental system to minimize the impact of such infectious outbreaks in the future.

1. Introduction

When the first report of Coronavirus Disease-2019 (COVID-19) appeared in December 2019 from Wuhan, China, it was naively treated as another flu-like sickness (Lai et al., 2020). Subsequently, China took unusual steps of a complete lockdown and isolation of the affected cities from the rest of the world. By February 2020, the SARS-CoV-2 virus, which causes COVID-19, had spread across the globe. The World Health Organization (WHO) officially declared COVID-19 a pandemic (TEAM, 2020). As of 1st November 2020, there have been 45,678,440 confirmed cases of COVID-19, including 1,189,945 deaths (WHO, 2020). The COVID-19 pandemic has proven that we share one planet’s atmosphere without boundaries. Scientists from all disciplines have contributed to furthering the understanding, forecasting, and mitigation of this and other outbreaks. Presently, four possible methods of SARS-CoV-2 transmission have been suggested: direct/indirect contact, droplets, airborne (by the formation of aerosols), and fecal transmission (Liu et al., 2020a; Nouri-Vaskeh and Alizadeh, 2020).

The speed and degree of the pandemic spread is stimulating questions for the air quality, energy, water supply, and sanitation sectors worldwide. The pandemic has also resulted in a widely reported climate benefit of cleaner air in many countries, including China and India (Amawi et al., 2020; Dutheil et al., 2020; Sharma et al., 2020). However, this temporary decline in pollution is not a sustainable way of cleaning
up the environment. The virus crisis brings other environmental problems that might last for a longer time and are harder to deal with. SARS-CoV-2 has been widely detected in domestic wastewater, raising severe threats to delivering safe water, sanitation, and hygienic conditions, particularly in regions where water and wastewater treatment infrastructure is less than ideal.

COVID-19 has created an unprecedented impact on the global economy. The oil and gas sector has been seriously impacted in recent months. The crisis can have impacts in multitude and can potentially transform the dynamics of the global market. It can derail the efforts made on renewable energy transition, and thus, can spark another debate on exploiting renewable vs. non-renewable energy resources. A de-bounce in oil consumption can be expected if the wave of COVID-19 eases soon. On the other hand, a prolonged viral wave of COVID-19 can further deepen the energy crisis. The prevailing scenario triggers the need to respond to this unprecedented crisis wisely and responsibly to minimize the damage. The later sections of the article focuses on the impact of COVID-19 on different aspects of the environment, water, and

![Aerosol optical depth (AOD) measurements over India during 31st March to 5th April period for each year from 2016 through 2020. The sixth map (2020 Anomaly) shows AOD in 2020 compared to the average for 2016–2019. Retrieved by the Moderate Resolution Imaging Spectro-radiometer (MODIS) on NASA’s Terra satellite 2020 (Ref. (Observatory, 2020) and reproduced not copyrighted material of NASA).](image-url)
energy sector and provides an understanding of the key issues to which environmental scientists and engineers can contribute.

2. COVID-19 and air quality

The spread and impacts of COVID-19 resulted in a widely reported unprecedented improvement in air quality. Several ground and satellite observations have shown cleaner air in developed and developing countries (Newburger and Jeffery, 2020). The cleaner skies do show how fast and how far human efforts can bring down pollution collectively when the emission budget is reduced significantly. However, attaining sustainable clean air cannot be attained by the restrictive rules and rolling back ambitious auto mileage standards (Friedman, 2020). The cleaner skies do show that global and collected societal efforts may indeed be able to reduce emissions substantially and sustainably to mitigate imminent climate change.

Overall, the crisis may consequently have no sustainable air quality improvement, but it shows a promise that our society can substantially reduce the risk of 7 million lives each year due to poor air quality even when no pandemic exists (WHO 2018). However, environmental benefits and risks of sharp drops in global activity will help humanity to understand the mechanics of sustainable ecological development, consumption and eco-friendly behavior to control air quality.

2.1. Current state of affairs

Air quality levels in the world’s major cities have been improved dramatically in March and April of 2020 (Observatory, 2020), during the first implementation of lockdown in most countries (Fig. 1). Air quality was improved primarily due to emissions reductions of particulate matter (PM2.5 & PM10), ozone (O3), nitrogen oxides (NOx), and carbon dioxide (CO2), from stationary and mobile sources (Regan, 2020). Mobility, a proxy of vehicular emissions, have decreased significantly in urban centers of the world. Commercial air traffic also dropped by 70% across the globe, which translates to a temporary dip in emissions equivalent to taking 6 million cars off the road and a 31% drop in carbon dioxide emission from their pre-pandemic levels (Powley, 2020). However, the levels of the greenhouse gas methane (CH4) are expected to rise sharply due to dis-improvement in municipal waste collection and processing with subsequent uncontrolled decay of waste, which is left to collect or process in cities.

This temporarily improved air quality could end up worse than before the pandemic. Polluting industries may seek higher production levels with relaxation in environmental regulations. Post-pandemic economies may prompt loosening of health-protective regulations, such as the US-EPA decision to all but suspend enforcement of pollution rules and rolling back ambitious auto mileage standards (Friedman, 2020a). The governments will be inclined towards quickly rebooting the available fossil fuel industry, and investments in wind and solar energy sectors are likely to drop. It is expected that more vehicles will be on the road due to imposed social distancing and consequently contribute to higher emissions.

2.2. Health significance

Prolonged exposure to air pollution has been linked to cardiopulmonary morbidity and mortality due to acute respiratory inflammation, asthma attack, and cardiorespiratory diseases in various studies (Friedman, 2020a). Improved air quality resulting from shutdowns have been estimated to have saved between 53,000 and 77,000 lives in China, many times more than the direct toll of the virus (based on > 1.2 million deaths per annum usually caused by the poor air quality in China (Burke, 2020; Institute, 2019)). Measures taken to clean the air during the Beijing 2008 Olympics had led to a drop of 8% in the overall death rate (He et al., 2016). Air pollution acts as a co-factor of indirect systemic effects within the human body, eliciting the pro-inflammation and oxidation mechanisms of the lungs, immunological alteration processes, and increasing the vulnerability of the COVID-19 exposed population (Contini et al., 2020). During the SARS-CoV-1 outbreak in China in 2003, patients in regions with moderate air pollution levels were more likely to die than those in regions with low air pollution levels (Cui et al., 2003), while a correlation between air pollution and COVID-19 severity in the USA has been noted (Friedman 2020b). However, prominent variability in the mortality were caused by 2009 influenza (H1N1) due to different regional factors. It was found that only 4% of the mortality was assigned to PM10 and that other factors had larger or comparable contributions (Morales et al., 2017).

A vital fact is the effect of the physicochemical properties of aerosol particles mediating the generation of inflammation and immunotoxicity in the human body. The possible routes of bioaerosol cytotoxicity could include oxidative stress, oxygen-free radical-generating activity, DNA oxidative damage, mutagenicity, and the stimulation of pro-inflammatory responses. However, the exact mode of toxicological mechanisms associated with aerosols are unclear (Contini et al., 2020). The role of smaller particles with aerodynamic diameters smaller than 0.1 μm (ultrafine particles), is also essential to consider health outcomes. The regional fatality levels of COVID-19 are varying significantly, with India, China, and Pakistan regions with poor air quality exhibiting lower mortality rates than other hard-hit countries. The world’s highest fossil fuel producing GCC (Qatar, UAE, Saudi Arabia, Oman, Kuwait, Bahrain) region of the Middle East, have also reported a lower fatality rate (Roser et al., 2020; WHO, 2020) (Fig. 2). Since the pandemic started, the apparent detrimental effect of air pollution on the prognosis of COVID-19 through invoking co-morbidities warrants further investigation.

2.3. Outdoor and indoor air

The existence of SARS-CoV-2 in air and the period for which it remains airborne is a subject of intense investigation. However, evidence-based studies elaborate that the smaller virus-laden particles (<5 nm in diameter) related to the respiratory emissions (aerosols from coughing, sneezing, respirators, etc. (>5 nm diameter) of infected individuals) could remain in the air for few hours, transported and dispersed by winds and turbulent eddies (Asadi et al., 2020). Further investigation is needed to ascertain the contribution of this mechanism as a possible route of spread and its weight compared to other transmission routes through direct contact via large droplets. The critical missing factors are effective concentration, viability, size, and life time of the virus in the air particulate matter. Biological and chemical composition of the virus-laden aerosols in the air is another important factor that needs to be considered.

Analytical techniques measuring the presence of nucleic acid sequences do not distinguish among viable or non-viable viruses. Further studies are needed to determine viral activity and viability in the collected samples. A recent study suggested that aerosolized SARS-CoV-2 remains viable in the air with a half-life in the order of 1 h in a laboratory-controlled environment (Kampf et al., 2020). However, the half-life would vary in ambient environments due to differences in temperature, relative humidity, and UV exposure. Liu et al. investigated a small set of samples from the ambient environment in public areas of Wuhan during the outbreak in February 2020 and found no detectable concentration except at two small crowded sites. Considering the average volume of air involved in respiration and the number of particles inhaled, it is estimated that small concentrations of the viable airborne virus in outdoor environments is very low (Liu et al., 2020a).
Given the general public recommendation to stay home and minimize social contact, indoor environments would require scrutiny. The risk of contagion via airborne virus-laden aerosols could be higher in specific indoor environments that are confined with lower ventilation rates, absence of dedicated return air channel, inadequate pressure. Heating, ventilation, and air-conditioning (HVAC) systems are known to play an active role in pathogen dissemination, if not adequately maintained and operated. Since there are no simple methods of detection and viability testing of the virus in the air, it is complicated and difficult to ascertain the role of HVAC in spreading the COVID-19 virus, but it cannot be ruled out completely. The small size of coronavirus particles (80–160 nm) enables them to stay airborne and potentially travel long distances through duct airflow. In addition, studies of the earlier outbreak of SARS-CoV-1 concluded that the HVAC system was a pathway of virus transmission (Booth et al., 2005; Li et al., 2005; Olsen et al., 2003). Earlier, the US Centre for Disease Control (CDC) reported an outbreak at a restaurant in Guangzhou, China, where ten peoplecontracted SARS-CoV-2. The study concluded that the HVAC prompted droplet transmission in the direction of the airflow (Jianyun et al., 2020). It has also been reported that SARS-CoV-2 has been isolated from swabs taken from exhaust vents of hospital rooms housing infectious patients (REHVA, 2020).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Federation of European Heating, Ventilation and Air Conditioning Association (REHVA) issued position and guidance documents for HVAC users and operators for the operation optimization during the COVID-19 outbreak (ASHRAE, 2020; REHVA, 2020). These non-pharmaceutical measures stress the use of higher supply air flow and exhaust ventilation and fixing a lower CO₂ set point (400 ppm). The houses and offices equipped with split units or windows unit air conditioning in hot and humid areas are likewise advisable to force the frequent natural ventilation according to the metrological conditions outside. REHVA stresses the exhaust system in washrooms should always be kept on because the aerosolization due to flushing could increase the risk, and recirculation mode should not be used to tradeoff the energy consumption during the pandemic period. Although temperature and humidity play a significant role in virus control strategies, the required temperature (34 °C) and humidity (60%–80%) are not within the comfort levels of the occupant. Leakages through heat recovery devices from exhaust air to supply air should be monitored to avoid the recirculation of any virus-laden particles to different parts of the building.

The risk of infection at public places in the indoor environment needs to be considered, due to the higher chances of airborne droplets, the buildup of concentration and stability of the virus, and the presence of more people. Therefore, it is critical for building operators and HVAC managers to carefully monitor the situation for the safeguarding of the occupants. The missing component of multidisciplinary research to investigate the particulates’ physicochemical and biological properties, toxicological routes, and mechanisms impacting human health needs to be addressed. Also, the information related to effective concentration and viability of the virus-laden bioaerosols, virus lifetime, and effectiveness of measurement techniques in non-laboratory environments is scanty.

3. COVID-19 and water

3.1. SARS-CoV-2 in the water cycle

Numerous outbreaks of various diseases induced by waterborne pathogenic viruses have been reported (Ganesh and Lin 2013; Kauppinen et al., 2018; Kitajima et al., 2014). It is critical to investigate the fate of this virus in different parts of the water cycle, including in surface water (estuaries, water channels, and rivers), the marine environment, and groundwater. Considering the recent studies on the persistent nature of the virus, the potential for SARS-CoV-2 to remain viable in water streams, including precipitation and groundwater infiltration through soil warrants investigation. Other coronaviruses including SARS-CoV-1, Middle East Respiratory Syndrome (MERS), and highly pathogenic influenza transmitted from human and animal feces have been reported in freshwater (Seidel et al., 2016). Detection of the virus in sewage (discussed in Section 2.2) highlights the persistence of this virus in aquatic environments and wastewater treatment plants (WWTPs). The presence and viability of SARS-CoV-1 in a different type of waters including surface water, sewage and wastewater have already been shown in earlier studies (Hung 2003; Leung et al., 2003; McKinney et al., 2006). Other studies reported the viability of coronavirus in feces for 4 h and water for weeks (Casanova et al., 2009; Weber et al., 2016).

In the absence of appropriate and persistent disinfection (such as chlorination), surrogate coronaviruses have been shown to persist for up to 10 days in filtered tap water at 23 °C and much longer in colder water (Casanova et al., 2009), with sorption to particulates providing a protective mechanism for the virus (Gundy et al., 2009), leading to concern over persistence in cool freshwaters which could be potentially drinking water sources. Environmental factors were concluded as a primary reason for the transmission of the SARS outbreak in Hong Kong during March 2003 (McKinney et al., 2006). However, data remain scarce about the impact of different environmental factors on stability and decay of SARS-CoV-2 in the various forms of water. Virus viability and persistence significantly depend on factors such as pH, temperature, water type; however, SARS-CoV-1 remained viable and infectious, particularly at lower temperatures. Comprehensive studies on the
transmission and fate of the SARS-CoV-2 virus in various types of interrelated environmental segments, including the aquatic environment, soil, and air, are necessary. It will also be essential to provide a better understanding of risk assessment in water and food nexuses. The future of risk assessment of the virus in the water cycle lies in representative sampling strategies together with swift and highly specific methods of SARS-CoV-2 samples preparation and detection. In addition, a particular focus needs to be placed on regions where drinking water treatment and disinfection are sub-standard.

3.2. SARS-CoV-2 detection in wastewater

The consequences of the pandemic on the water sector has critical global implications. A number of case studies have reported the detection of live virus or viral RNA in the feces of some patients with SARS-CoV-2 infection (Liu et al., 2020b; Wong et al.; Zhang et al., 2020a; Zhang et al., 2020b). Those patients were initially diagnosed with COVID via nasopharyngeal swabs. However, while upper respiratory swabs turn negative after a certain period, the virus continues to be detected in rectal swabs or fecal samples in a high proportion of patients (typically 50–80%) for a much longer time, in some cases more than 20 days, with viral shedding from the digestive tract potentially being more persistent than previously thought (Chen et al., 2020; Effenberger et al., 2020; Hindson, 2020; Xu et al., 2020). This has suggested fecal-oral transmission as another possible route of virus transmission, along with aerosolization from toilet flushing in homes and in wastewater treatment, with coronaviruses estimated to survive in sewage for approximately 3 days (Gundy et al., 2009; Nghiem et al., 2020) (Fig. 3).

Studies are being conducted all over the world to investigate the occurrence of SARS-CoV-2 virus in sewage and wastewater treatment plants (WWTP). The presence of the virus in the sewage had already been reported in preliminary investigations performed in the Netherlands followed by virus detection in WWTPs in USA, Australia, France and Italy (Ahmed et al., 2020b; La Rosa et al., 2020; Lodder and de Roda Husman 2020a; Medema et al., 2020; Wu et al., 2020; Wurtzer et al., 2020a). Therefore, the quantification of the virus in wastewater offers an excellent opportunity to monitor the prevalence of infections among the population (Ahmed et al., 2020a; Lodder and de Roda Husman 2020b). SARS-CoV-2 has also been identified in a small number of treated wastewater samples, albeit at concentrations 100 times less than the concentration observed in the untreated wastewater samples (Wurtzer et al., 2020b). The presence of the virus in treated water should be a matter of great concern and depicts the inefficiency of some current treatment processes to completely remove the virus from wastewater. This is of particular concern in areas where untreated or poorly treated discharge to surface water bodies is commonplace, given the potential persistence of the virus in freshwater outlined in Section 2.1.

3.3. Wastewater-based epidemiology (WBE) for COVID-19

The characterization of sewage chemical and biological contents can provide important information about public health. The technique of identifying biomarkers for human health in wastewater, and mapping that back to risk and hazard exposure in a population, is generally known as wastewater-based epidemiology (WBE). It has been found that 50–75% of patients infected with SARS-CoV-2 are asymptomatic, clearly a bottleneck for controlling the pandemic (Day 2020a, 2020b), as these patients may not be a high priority in the selection of candidates for screening studies. However, these patients would be detected in the population using WBE. Theoretically, identification of one symptomatic/asymptomatic patient per 100–2,000,000 non-infected population is possible; however, several environmental parameters make it difficult to analyze in community wastewater (Hart and Halden 2020) (Fig. 4).

WBE studies could be an important area of research for the early detection of COVID-19. Research should focus on developing fast, direct, and accurate detection of the virus, not only in clinical samples but also in the environmental matrices. The currently used nucleic acid-based PCR methods for virus detection in sewage samples are complex and involve relatively high costs of time and man-power. Currently, there is no unified standard method available for the qualitative and quantitative analysis of the virus; however, there are global initiatives for protocol harmonization underway including by the NORMAN network and the recent EU Call Notice (EU and Environment, 2020). The development of virus detection methods has several challenges including the low concentration of the virus in WWTP, complex sewage matrix, and development of sample collection protocols in addition to detection of the host origin of the virus. Advanced sensing technologies could be a smarter approach to detect the virus in sewage and WWTPs. For

![Fig. 3. Possible fecal-oral transmission of SARS-CoV-2. Water/wastewater surfaces and places with vectors can be possible transmission routes. (Adapted from Ref. (Heller et al., 2020) and reproduced with permission of Copyright © 2020 from Elsevier).](image-url)
example, on-line sensors can be developed for detecting the virus based on the biomarkers allowing a rapid, cheap, and reproducible detection and quantitation of SARS-CoV-2 in municipal wastewater. Several low-cost paper-based sensors have been developed for efficient detection of pathogens such as HIV, rotavirus A, Zika virus, E. coli, etc. Similar paper-based sensors are being investigated as a small, portable device to detect SARS-CoV-2 in sewage (Mao et al., 2020).

Modeling of obtained population-wide data can help to predict the current and future behavior of infectious diseases and is an important research area to address. However, extensive research is required to overcome the challenges associated with wastewater based epidemiological modeling. For example, it is very difficult to obtain reliable estimates of key kinetic data for the model. The kinetics rely heavily on the behavior of the virus in the sewer network (residence time and flow, interaction with biofilm, the pathway through pumping stations, risers, etc.), the impact of temperature, pH, presence of inhibitors and RNAses, etc. In addition there is significant uncertainty and variability in the amount of viral material present in the patient fecal matter as the disease progresses, which varies from patient to patient but also from day to day in a single patient. In addition, composite samples which are representative of the population being sampled are critical for interpretation of the data obtained; these can be difficult to obtain for practical and logistical reasons for certain populations of interest (for example schools).

3.4. Viral disinfection and sludge disposal

Disinfection protocols and regulations already exist to predict a broad spectrum of pathogens, including bacteria, viruses, and protozoa in drinking water treatment systems and WWTPs. Coronavirus is spherical or pleomorphic, single-stranded, enveloped RNA and covered with club-shaped glycoproteins including the spike protein responsible for the facilitation of targeting of ACE-2 receptors in various organs (Amawi et al., 2020; Wrapp et al., 2020). Like many other enveloped viruses, it is believed that existing disinfection methods can sufficiently remove SARS-CoV-2 during the wastewater treatment process. According to recent guidelines released by Occupational Safety and Health Administration (OSHA) for sanitation workers and the public, traditional and emerging disinfection technologies such as chlorination, ozonation, ultraviolet irradiation, and other advanced oxidation processes employed in WWTPs are expected to be effective in inactivation of SARS-CoV-2. However, ineffective treatment and failure of such barriers can spread the virus through the distribution systems.

Additionally, more than 80% of the wastewater produced worldwide and over 95% in some least developed countries is discharged to the open environment without any treatment (IWA 2018). As the pandemic has already spread throughout the world, the implications for the water sector throws a harsh spotlight on the existing inequalities. Billions of people worldwide do not have access to sanitation and consequently safe water, with potentially disastrous consequences for drinking water and hygiene in the context of this pandemic.

Continuous monitoring of the treated water quality is necessary to ensure effectiveness of the viral disinfection process. Online wireless monitoring devices could be used to ensure proper working of equipment/sensors analyzing different water parameters at the outlet of WWTP. Currently many kinds of buildings, including hospitals, hotels, conference halls, school buildings, etc. have been repurposed as quarantine or temporary medical facilities, and filled with thousands of suspected patients. The plumbing of these buildings was never designed for the safe disposal of clinical waste. Faulty plumbing and poor building infrastructure may lead to substantial and broader contamination. The threat is even higher in hospital wastewater. Small-decentralized WWTPs could be an excellent option to manage such outbreaks better.

Activated sludge-type processes, including membrane bioreactors, are commonly employed for the secondary and advanced treatment of domestic wastewater. These biological secondary treatment technologies are capable of pathogen reduction and can have a vital role in removing the SARS-CoV-2 virus from effluents (Delanka-Pedige et al., 2020). Activated sludge is a very complex microbial system in which inactivation of enveloped viruses including corona, polio and other viruses has been reported due to competition of microorganisms and unsuitable physicochemical conditions for virus survival (Amarasiri et al., 2017; Bodzek et al., 2019; Chaudhry et al., 2015; Ward 1982). Conversely, viruses and other microorganisms can be concentrated in the sludge. WWTPs employing activated sludge processes produce high volumes of sludge, and the presence of SARS-CoV-2 can be expected in
the biosolids discharged from the WWTPs, which may pose another threat to public health. It requires a careful strategy to treat/dispose of the sludge to avoid any contamination of the virus present in the solids. Sludge generated by WWTPs requires suitable disinfection before its disposal, which is typically via high-temperature thermal drying; most countries are already well regulated for pathogen reduction in sludge (Pepper et al., 2006). However, although likely to be low risk, there is currently no data confirming the inactivation of SARS-CoV-2 in WWTP biosolids either before or after post-treatment processes. The presence of SARS-CoV-2 in the landfill biosolids could result in its transmission to soils and receiving water bodies. Research data on the viability and concentration of SARS-CoV-2 in sludge is critical to conduct quantitative estimates of risks posed by the sludge/biosolids.

3.5. Aerosolization of SARS-CoV-2 in WWTP

The potential for on-site exposure to aerosolized pathogens is maximized for biosolids workers involved in loading and unloading biosolids, and also during land applications. There are several reports about air spread of the SARS-CoV-1, a predecessor of novel SARS-CoV-2, in indoor and outdoor environments. The airborne transmission was explained as a possible pathway of transfer in the indoor environment of several health care facilities and aeroplanes (Booth et al., 2005; Olsen et al., 2003; Xiao et al., 2017). The rapid spread of SARS in a large apartment complex in Hong Kong in 2003 was primarily assigned to the virus aerosolization in the toilets and then rapidly spread in all the apartments due to the poor plumbing (McKinney et al., 2006).

In a recent preliminary study on the resilience of SARS-CoV-2 carried out by quantitative measurement of viral airborne efficiency in the air chamber, it was found that SARS-CoV-2 was persistent in aerosol form and almost no decay recorded for 16 h (Fears et al., 2020). Although a lab study in a controlled environment, this provides a preliminary understanding that this virus is potentially viable as an airborne pathogen. The formation of droplets and aerosolization of the pathogens from wastewater could be a major source of spread. There are examples of aerosolization of several pathogens from water such as Legionella, Cryptosporidium, Norovirus, and Hantavirus, resulting in ingestion or inhalation of the virus (Brisebois et al., 2018; Mirzaei et al., 2015; Pascual et al., 2003; Pillai, 2002; Yazdanbakhsh et al., 2020) (Fig. 5).

Virus transmissions via fecal oriented aerosols become more likely if SARS-CoV-2 is persistent and remains viable for an extended period in water. Currently, real data is scarce about the patterns of infections and airborne transmission of SARS-CoV-2; however, multiple cases of non-contact transmission have been reported particularly in Hunan and Tianjin regions outside of Wuhan (Morawska and Cao, 2020). The presence of the virus in WWTPs can result in the formation of bio-aerosols due to aerosolization. Airborne transmission of virus produced from WWTPs may have a significant impact on plant workers and the surrounding communities in the urban area. Moreover, workers involved in loading/unloading and disposal of sludge biosolids could be at greater risk due to on-site exposure to aerosolized SARS-CoV-2 virus. Detailed studies are needed to find out the survival of the virus in indoor and ambient air in different environmental conditions, together with the airborne fecal droplet transmission model to understand the health risk associated with SARS-CoV-2 in future.

3.6. Increased wastewater loadings and concentrations

Hand washing by soap and water are the main measures recommended by the WHO to avoid transmission of COVID-19 (Tabish and Basch, 2020). Increased handwashing and adhering to basic hygiene principles during COVID-19 is expected to increase daily domestic water requirements. It becomes much more complex and poses serious consequences in the water-scarce regions of the planet where people already 

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![Fig. 5. Distribution of human viruses in aerosols samples collected from sampling locations from three different sites of a WWTP in Canada. Samples were analyzed by metagenomic analysis. Human viruses, including adenovirus (hAdV), rotavirus, hepatitis A virus (HAV), and Herpes Simplex virus type 1 (HSV1) were detected in the aerosolized form (Ref. (Brisebois et al., 2018) and reproduced with permission of Copyright © 2017 from Elsevier).](image-url)
lack access to clean water. For instance according to United Nations Economic and Social Commission for Western Asia (ESCWA), for water-scarce Arab countries, domestic water demand is expected to increase by 4–5 million cubic meters per day where about 87 million people already lack access to clean drinking water (ESCWA, 2020). While currently there is no evidence of transmission of COVID-19 in drinking water supplies, still SARS-CoV-2 has a significant impact on the water sector in numerous ways.

Production of domestic wastewater is also expected to increase and change in pattern, with higher loadings of surfactants and different sorts of disinfectants and their byproducts. Timing of peak loads to WWTPs have been shown to have shifted due to remote working and social distancing, and lack of clarity on safety and aerosols, lack of advanced PPE and staff, working skeleton shifts where possible have all impacted on operations (Ike, 2020). Surfactants and detergents are generally well removed during aerobic treatment (Zhu et al., 2016); however, higher input may necessitate increased energy input due to longer residence times or increased air flowrate in blowers, and the chance of transmission to the environment is significant during high loading (Freetling et al., 2019; Zhu et al., 2019). While antibacterial compounds that are resistant to breakdown in WWTPs such as triclosan or triclocarban are not used in many countries, the increase in usage of hand sanitizers and disinfectant soaps (many produced in countries with less stringent regulation) may lead to transmission into receiving waters (Pycke et al., 2014). Further, the extensive use of disinfectants could be a concern for the proliferation of ARB/ARG (anti-microbial resistant bacteria/genes). There is an urgent need to develop and communicate the procedures for safe and sustainable management and disposal of bleaches and disinfectants, particularly for regions with limited wastewater treatment capacities.

4. COVID-19 impact on energy resources

4.1. Energy resources and oil economy

The global oil economy is witnessing an unprecedented shock due to COVID-19. Oil demand has witnessed a dramatic decline in industrial, commercial, domestic, and transportation uses. It has led to enormous pressure on balancing supply and demand and storage to control oil prices. Global oil demand is expected to fall by 9.3 mb/d year-on-year in 2020. Demand in April 2020 was estimated as 29 million barrel/day (mb/d), which is below the level observed in 1995. Global oil supply plunged by 10 mb/d in May 2020 to a nine-year low of just under 89.9 mb/d, as the OPEC+ agreement took effect and production declined elsewhere. Total OECD oil stocks have stood at 42.4 mb and crude oil storage increased to 103.1 mb in March 2020. Overall, oil prices decreased by 40%. The Brent price reached at a certain point USD 31/bbl, while the West Texas Intermediate (WTI) and West Canadian Select fell below USD 10/bbl. The oil and gas income of the major oil-producing countries is expected to fall 50–85% in 2020 as compared to 2019, representing the lowest oil-based income in the last two decades. For instance, Ecuador’s income would fall 85% in 2020 as compared to 2019.

Oil-producing countries have been striving hard to recover the economic damage from 2014, and it is evident that COVID-19 has further deepened this crisis. The Gulf is also observing a fiscal deficit of 10–12% of GDP this year, demanding an injection of USD 150–170 billion. Globally, oil companies have reduced their production by 20–35% of what they had predicted in 2020, with a major squeeze on the volume of the refining industry (IEA, 2020c). A climax of the oil crisis was observed on 20th April 2020, when oil prices turned negative in the US, claiming what they had predicted in 2020, with a major squeeze on the volume of GDP this year, demanding an injection of USD 150 billion. Meanwhile, oil importing countries would have taken advantage of the low-price oil period to support their economies (Egan, 2020). The crisis would result in a major cut or delay in other on-going or future development projects on hospitals, road, hotels, tourism, industries, power production, education, and many others. A prolonged period of low oil prices would not only slash the conventional energy resources but could also bring a paradigm shift in renewable resources. It could lead to shifting economic reliance from oil to other alternative commodities (Gould and Al-Saffar, 2020). Thus, it is a crucial for the oil companies to respond strategically and provide more innovative, economical, and sustainable solutions to frame the future roadmap.

4.2. Carbon footprint

Global confinement in the last few months not only reduced the spread of COVID-19 and death toll but also reduced carbon emissions by almost 9% in the first half of 2020 (Liu et al., 2020b). It is estimated that transport accounts for 20% of global CO2 emissions, power industries 38%, and buildings 9%, (WorldoMeter, 2020). Thus, less carbon emission at the time of COVID-19 can be attributed to the less use of transportation and reduced industrial activities. It is too early to conclude that this decrease in carbon emissions will have a sustainable impact on climate change (Macola, 2020), as a resurgence in CO2 emission can be expected as soon as travel restrictions and lockdown measures are eased. In 2008, a fall in emissions by 1.3% was noted, but it rebounded as the economic activities were recovered. In late March 2020, emissions in China rebounded due to the restart of industries.

Lock-down has dramatically improved the use of electronic resources to foster communication. Streaming contributed to 300 Mt CO2 in France in 2018, highlighting its severe impact on the global climate (Efoui-Hess, 2019). The energy consumed using Netflix for 1 h is equivalent to driving a Tesla Model S 30 km, or powering an LED bulb for one month (Efoui-Hess, 2019). However, Kamiya et al. present a rebuttal to these statistics claiming that this estimation was exaggerated and contains major flaws in analyses of data transferred in each second during streaming (Kamiya 2020). It is unveiled that energy consumption during live streaming highly depends on network choice, device efficiency, and design specifications, for example, an LED TV consumes much more electricity than a smartphone or laptop. Streaming 4G mobile consumed four times as much energy than WiFi. They further added that 30 min of streaming would release 0.028–0.057 kg CO2 rather than 1.6 kg. Regardless of the level of severity of live streaming, it is plausible that it contributes to a rise in CO2 emissions. Further estimations should be provided to reflect the contribution of live streaming to CO2 emissions during the COVID-19 outbreak.

4.3. Progress on renewable energy resources

Transitions to renewable energy technologies (RETs) have been rigorously followed in the last two decades to meet environmental and ecological regulations (Köhler et al., 2019). A few months ago, 2020 was considered a record-breaking year for renewable installations (Fox-Penner, 2020). Global demand for solar and wind energy was set to increase by 20% across the world (Bahr, 2020). Before COVID-19, the deployment of RETs was expanding and developing supply chains to
The COVID-19 effect has also rippled through the renewable energy industry, with drops in investments, staff layoffs, and is likely to bring changes in on-going progress and outlook of RETs. COVID-19 has halted industrial, commercial, and transport activities, which consume a major chunk of global electricity (Singh, 2020). Reduction in electricity demand would have a direct impact on the installation of new RETs. A decline in solar energy installations up to 17–48% is expected in 2020, with solar panel production slowdowns in India, Australia, and China (Singh, 2020). In India, an 18% reduction in wind installations and 20% cut in solar installations are being projected, as compared to the last year. In Europe, the supply chain of solar PV and wind have been disrupted. Construction activities for renewable installations have been slowed or shut down due to lockdown (Bahar, 2020; Chandrasekaran, 2020). Manufacturing in Italy, Spain and several other European countries has been suspended due to lockdown measures (Welle, 2020).

The utilization of ethanol has also decreased, which is used as a 10% blend with gasoline (Mintert, 2020b). It has resulted in a decrease in ethanol demand and price. The demand for biodiesel is also expected to decrease in the upcoming months (Mintert, 2020b). Diesel is mostly used in heavy-duty trucks, agricultural machinery, and construction types of equipment, unlike gasoline, which has versatile utilities. Thus, it is estimated that the reduction in the demand for diesel would be half that of gasoline. The need for biodiesel can decline up to 219 million gallons in 2020, which is 13% of 2019 US biodiesel production (Mintert, 2020b). Employment in clean energy has been the fastest-growing sector in the last decade. Approximately 3.4 million jobs were accounted for the clean energy sector. However, over 600,000 workers in the US clean energy sector had lost their jobs by June 2020. Prolonged lock-down and economic recession can spur a reduction in RETs use. Supply chain disruption is another reason to affect RETs installation in near terms due to delayed deliveries or less demand.

As low oil prices will mount enormous pressure on renewable energy economics; eventually transition to clean energy will be slowed despite the immediate need. After recovery from COVID-19, a shift in the energy supply chain is being anticipated (Lanng, 2020). Oil importing countries would prefer to generate electricity through oil sources to provide temporary support to their dwindling economies instead of adopting RETs. The policymakers will confront a difficult situation to accelerate or at least continue efforts on RETs or take advantage of cheap fossil fuels at the cost of environmental damage. The current wave of COVID-19 can severely affect the global investments on RETs (Energy, 2020). It has urged the policymakers to make resilient plans covering a sizeable investment in the renewable energy sector.

An International Renewable Energy Agency (IRENA) report states that accelerating the use of renewables for decarbonization can support a short-term and resilient recovery from the COVID-19 damage. Investments should continue promoting power grids, energy storage, green hydrogen, and other technologies (IEA, 2020a). The use of clean energy for the sustainable global economy and environmental regulations should be advocated at every policy forum, being a step forward to improve the cost competitiveness of RETs. Otherwise, delayed attention or slow growth of RETs and rethinking the ambition of transitioning to renewable sources would be the biggest shock to global sustainable development. In contrast to the aforementioned analysis, 15% increase in wind energy was observed in March 2020 as compared to March 2019 (REVE, 2020). It shows a fall in electricity demand due to COVID-19 leading to a decrease in CO2 emissions, which is usually low during this time of the year.

4.4. Recovery plan

Governments in various countries are planning stimulus plans to recover damage incurred due to COVID-19. They are confronted with three issues at the same time (i) public health (ii) economic recovery, and (iii) climate change. Long-term and sustainable investment in public health would be the utmost priority. However, a trade-off between economic recovery and climate change could be considered. Economic recovery using fossil fuels would provide temporary relief; however, the climate change agenda will be compromised. IEA pointed out that low oil price favors consumers, but it gives only a little benefit to the people under lockdown.

In these circumstances, the importance of RETs should be realized in the context of energy security and climate change instead of short-term economic benefits. Efforts on decarbonization should continue by exploiting the use of RETs. In the time of lockdown, when the people worked from home and education was imparted through an online system, a massive amount of electricity was consumed. In the future, a rise in electricity demand can be expected, urging a sustainable production system. RETs can be well integrated with digital technologies to fulfill future electricity demand. The recovery plan should include investing in three emerging clean technologies, including hydrogen, batteries, and carbon capture (Birol, 2020a,b). Moreover, future RETs plans should align with broader clean energy goals that can foster employment and economic recovery. The exploitation of solar and wind energy can provide flexibility and sustainability to electricity networks. For example, wind energy can be useful in the nighttime when demand is low, and solar systems can be switched on during peak hours (Fatih Birol, 2020a,b).

Working on energy efficiency can offer multifaceted benefits such that it can create job opportunities, especially in manufacturing, can improve energy use efficiency, and support the economy by lowering bills (Apostolos et al., 2013; Belussi et al., 2019; Kumar and Zare, 2019). The existing houses, hospitals, schools, industries, commercial markets, etc. should be renovated and transformed into energy-efficient designs. The buildings should be equipped with efficient heating, cooling, lighting, and energy storage systems (Oppermann, 2020). In a broader perspective, energy efficiency projects should include replacing inefficient electrical appliances and construction materials and upgrading energy utilization in trains, cars, vans, etc. India upgraded 11 million streetlights with LEDs creating 13,000 jobs, and 5 million tons reduction in greenhouse gases in nine years. Indeed, the transition to energy efficiency involves capital investment and extensive labor work. The stimulus plan should include providing subsidies on energy efficiency projects (Belussi et al., 2019; Oppermann, 2020).

Energy production through anaerobic digestion (AD) which involves the production of methane by metabolizing organic waste materials has received widespread attention. Unlike wind and solar, AD is less prone to weather changes. AD can be more reliable and sustainable technology due to the ample availability of its feedstock i.e. waste resources. IEA has reported that AD can cover 20% of world gas demand (Cecarelli, 2020). Since waste amenable to AD is a distributed source across the world, bio-methane offers a decentralized system in contrast to fossil fuels. The scale-up application of bio-methane would demand a proper storage and grid system at a place for a sustainable and uninterrupted supply. Bio-methane can be complemented with the existing electricity system along with wind and solar systems to meet peak hour demand (Gunes et al., 2020; Gunes et al., 2019; IEA, 2020c).

Bioenergy with carbon capture and storage (BECCS) and direct carbon capture from the atmosphere could play a vital role in transitions to RETs. Improvement in land management practices and mechanized agriculture should be promoted, which would lead to store carbon in the soil instead of releasing it into the atmosphere through conventional agricultural practices (Budinis, 2020). The economic crisis of 2008 has taught us that spending on RETs positively contributed to economic recovery. A spectacular increase in wind and solar energy was observed, which contributed towards the sustainability of energy systems (Birol, 2020a,b). The government stimulus helped in the rapid progress of clean technologies, making them relatively cost-competitive.

In the current scenario, there is an immediate need to bring a clear long-term future policy to remove investors’ doubts (Birol, 2020a,b). To
meet these pressing goals, the plans should incorporate ambitious, cost-effective energy efficiency, underpinning the response to COVID-19.

5. Prospects and recommendations

The outbreak of COVID-19 has jolted the world ecosystem and unveiled inherent weaknesses in the existing infrastructure. The COVID-19 impact on global health has been widely observed, discussed, and analyzed in the last few months. It has fueled a debate on global health and driving the global economy. COVID-19 interrelated components of the ecosystem. They play a vital role in maintaining the ecosystem and driving the global economy. COVID-19 has triggered the need for addressing these issues together while outlining the future roadmap. Since COVID-19 has been declared a global emergency, therefore, future plans should be prepared in a more comprehensive and global context beyond the national interests only.

Air pollution levels decreased in the last few months due to global confinement. It provides an understanding that through joint efforts, climate change goals can be achieved. In the meantime, it should be noted that this is only a temporary relief, and thus, cannot be declared as a sustainable way of saving the environment. A relaxation in lockdown would increase air pollution as it is already witnessed in China and other countries. The air pollution level could even potentially be expected to cross pre-2020 levels. The reasons are two-fold (i) an abrupt increase in transportation and industrial activities to overcome the backlog (ii) use of more fossil fuel sources and relaxation in emission control legislation to support the economy. Some countries have already provided a notion to relax environmental standards to use fossil fuels and withdraw their commitments to using clean technologies for the short-term, at least. It can jeopardize the efforts made in the last two decades to transition to environmentally friendly and sustainable technologies. There is an urgent need to dispel this uncertainty by coordinated efforts and negotiations among the stakeholders. A consensus across the globe should be developed to mitigate the economic damage due to COVID-19 without compromising on the environmental agenda. A post-COVID-19 scenario may revolutionize the industrial process, working standards, environmental regulations, and revamp or upgrade existing infrastructure.

In the following, we present the recommendations evolved through the discussion provided in this article. It might provide a baseline to the scientists, researchers, policymakers, leaders, and other stakeholders while laying out a future roadmap to overcome the detrimental effects of COVID-19. Several specific areas that need to be focused on and addressed could include the fate and behavior of the virus in various supply routes, including air, soil, and water resources. Studies are needed to investigate airborne transmission of the virus. There is a need to investigate aerosol dynamics in an indoor and outdoor environment and to unveil an underlying correlation (if any) between air pollution control and COVID-19 outbreak. Propagation of the use of wastewater-based epidemiology could be a key for early detection of COVID-19. The need for ensuring compliance and access to safe water for each individual, notably underdeveloped regions, shall be a priority agenda. Filling the need for Investment in clean technologies could overcome unemployment quickly. Post COVID-19, there would be a need to critically reflect on ourselves and take necessary actions to make this planet a better place to live as the world would be trying to recover slowly from the COVID-19 effects. Multidisciplinary research is essential to investigate the aerosols’ physicochemical and biological properties, toxicological routes & mechanism, viral transformation, and lifetime in different environmental matrices.

Author contributions

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