

A case study of SARS-CoV-2 transmission behavior in a severely air-polluted city (Delhi, India) and the potential usage of graphene based materials for filtering air-pollutants and controlling/monitoring the COVID-19 pandemic

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1 **Secondary transmission of SARS-CoV-2 through wastewater: Concerns and**
2 **tactics for treatment to effectively control the pandemic**

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25

26

27 **Abstract**

28 The SARS-CoV-2 virus has spread globally and has severely impacted public health and
29 the economy. Hand hygiene, social distancing, and the usage of personal protective equipment are
30 considered the most vital tools in controlling the primary transmission of the virus. Converging
31 evidence indicated the presence of SARS-CoV-2 in wastewater and its persistence over several
32 days, which may create secondary transmission of the virus via waterborne and wastewater
33 pathways. Although, researchers have started focusing on this mode of virus transmission, limited
34 knowledge and societal unawareness of the transmission through wastewater may lead to
35 significant increases in the number of positive cases. To emphasize the severe issue of virus
36 transmission through wastewater and create societal awareness, we present a state of the art critical
37 review on transmission of SARS-CoV-2 in wastewater and the potential remedial strategies to
38 effectively control the viral spread and safeguard society. For low-income countries with high
39 population densities, it is suggested to identify the virus in large scale municipal wastewater plants
40 before following up with one-to-one testing for effective control of the secondary transmission.
41 Ultrafiltration is an effective method for wastewater treatment and usually more than 4 logs of
42 virus removal are achieved while safeguarding good protein permeability. Decentralized
43 wastewater treatment facilities using solar-assisted disinfection methods are most economical
44 and can be effectively used in hospitals, isolation wards, and medical centers for reducing the risk
45 of transmission from high local concentration sites, especially in tropical countries with abundant
46 solar energy. Disinfection with chlorine, sodium hypochlorite, benzalkonium chloride, and
47 peracetic acid have shown potential in terms of virucidal properties. Biological wastewater
48 treatment using micro-algae will be highly effective in removal of virus and can be incorporated
49 into membrane bio-reaction to achieve excellent virus removal rate. Though promising results have

50 been shown by initial research for inactivation of SARS-CoV-2 in wastewater using physical,
51 chemical and biological based treatment methods, there is a pressing need for extensive
52 investigation of COVID-19 specific disinfectants with appropriate concentrations, their
53 environmental implications, and regular monitoring of transmission. Effective wastewater
54 treatment methods with high virus removal capacity and low treatment costs should be selected to
55 control the virus spread and safeguard society from this deadly virus.

56 **Keywords:** COVID-19, Wastewater, Disinfectants, Secondary transmission, Wastewater
57 Treatment

Abbreviations

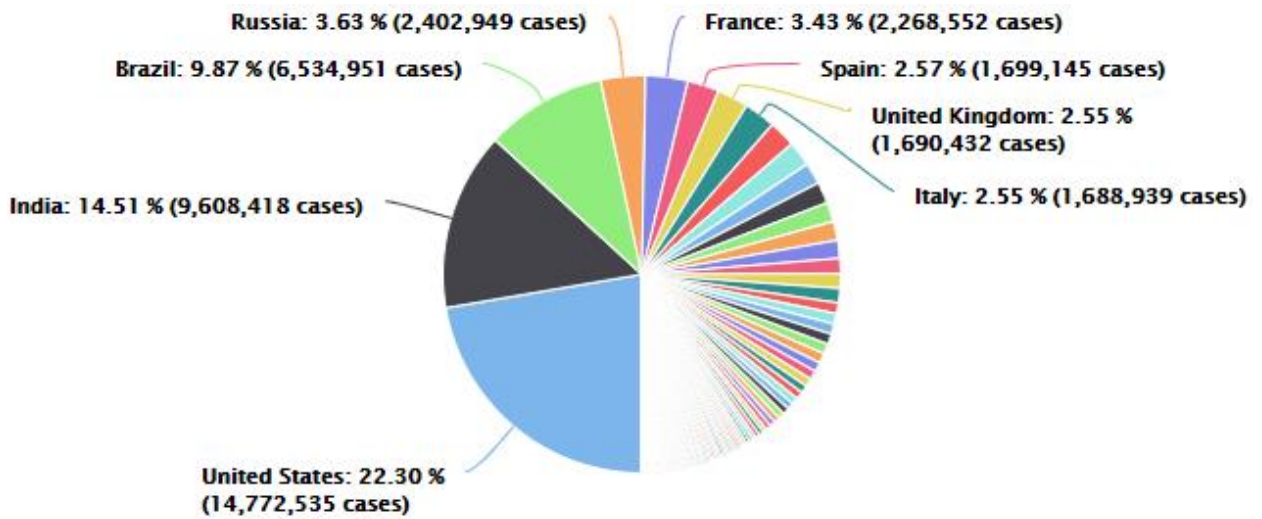
C/N	Carbon to nitrogen loading
COVID-19	Coronavirus Disease 2019
DNA	Deoxyribonucleic acid
LRV	Log Reduction Value
MERS	Middle East respiratory syndrome
MHV	Mouse hepatitis virus
MID	Minimal infectious dose
ORF	Open reading frame
PFU	Plaque-forming units
RNA	Ribonucleic acid
RT-PCR	Real-time reverse transcription polymerase chain reaction
RT-qPCR	Reverse transcription-quantitative polymerase chain reaction
SARS-CoV	Severe Acute Respiratory Syndrome Coronavirus
SARS-CoV-1	Severe Acute Respiratory Syndrome Coronavirus 1
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2

UF	Ultrafiltration
UV	Ultraviolet;
WHO	World Health Organisation

58

59 **1. Introduction**

60 The newly identified coronavirus disease ‘COVID-19’ was first identified as a pneumonia
61 virus causing respiratory illness which is thought to have originated from a local seafood market
62 in Huanan, Wuhan, China and was named ‘SARS-CoV-2’ by the World Health Organization
63 (WHO) on 12th January 2020. The WHO declared COVID-19 as a worldwide health emergency
64 on 30th January, and later, it was declared a pandemic on March 11, 2020. This SARS-CoV-2 has
65 spread across 210 countries and 66,231,472 confirmed cases and 1,524,473 deaths were reported
66 by December 5, 2020 as shown in Fig. 1 (Worldometer, 2020). The SARS-CoV-2 virus is a
67 pleomorphic ribonucleic acid (RNA) virus, belonging to the coronavirus family having crown-
68 shape peplomers (size - 80 to 160 nm) with positive polarity (27 – 32 kb) (Sahin et al., 2020).
69 COVID-19 virus genome sequence is 96.2%, similar to the ‘BatCoV RaTG13’ bat coronavirus
70 (Yan et al., 2020) and a low mortality rate of ~ 2 %.



71

72 Fig. 1. COVID-19 confirmed cases and their distribution country wise, as of 5th December, 2020.

73 However, the spreading rate of COVID-19 amongst humans is higher than SARs and MERS, with
 74 an incubation time of 24 days (Yan et al., 2020). The major path of transmission of the COVID-
 75 19 virus among humans occurs through inhalation of saliva and sputum droplets along with person-
 76 to-person physical contacts (WHO, 2020; Kitajima et al., 2018). Recently, Doremalen et al. (2020)
 77 compared the surface stability and aerosol transmission behavior of SARS-CoV-2 and
 78 SARS-CoV-1 and illustrated that SARS-CoV-2 can stay suspended for three hours in the air
 79 (Suthar et al., 2021), with an identical drop in its rate of infections compared to SARS-CoV-1. It
 80 was also revealed that the properties of SARS-CoV-2 and SARS-CoV-1 are identical in terms of
 81 the formation and air particles stability. Nevertheless, human receptors affinity for the initial
 82 variant of SARS-CoV-2 is 10 times greater than SARS-CoV-1. Several studies have shown that
 83 the COVID-19 virus can also be shed in feces from infected patients displaying acute symptoms,
 84 from asymptomatic individuals, and from patients cured without any further symptoms (Dhama et
 85 al., 2021; Pan et al., 2020; Tang et al., 2020; Xiao et al., 2020). In addition, COVID-19 viral RNA
 86 was detected in urine samples of infected patients (Ling et al., 2020). COVID-19 RNA was also

87 reported in the community wastewater and hospital sewage (Lodder and de Roda Husman, 2020).
88 Although the risk of spread of COVID-19 virus to people through water including wastewater is
89 still not clear, the identification of COVID-19 virus RNA in both treated and untreated wastewater
90 (Venugopal et al., 2020) raises the alarming situation of the potential for virus transmission
91 through this medium, and consequent occupational exposure concerns for wastewater treatment
92 plant workers. The potential for transmission of viruses through water bodies is gaining attention
93 recently among the research community, following the immediate response to the current
94 pandemic which predominantly focused on prevention of transmission from person-to-person. The
95 increasing number of testing facilities, hospitals, isolation wards and research centers developed
96 worldwide was essential to expedite the detection of infected patients and accommodate them for
97 further testing and to carry out advanced research about this new deadly virus. It is quite obvious
98 that these facilities have increased the generation of wastewater contaminated by the virus, and
99 that if incorrectly handled this will certainly pose a threat to society. Virus transmission through
100 wastewater might be a major worry in regions where there is a lack of water treatment facilities
101 and inadequate sanitation. In countries with lower income, domestic wastewater is often released
102 directly into the environment and may over time find its way towards groundwater (Omosa et al.,
103 2012). As the majority of people fulfill their water needs using groundwater sources in rural and
104 peri-urban areas (Kookana et al., 2020), the potential community transmission of the
105 SARS-COV-2 virus through infected and untreated groundwater is thus possible.

106 Apart from direct contact with wastewater, breathing of droplets/aerosols which are
107 contaminated with infectious viral particles is considered as the major source of virus transmission
108 in wastewater treatment plants. However, given that this is the first pandemic on such a global
109 scale, very few studies have taken into consideration the risks posed to wastewater treatment plant

110 workers and hence, there is a tremendous need to investigate and highlight the potential of this
111 exposure route as a route of infection. Even though it is stated that the existing disinfection
112 methods can deactivate viruses in water bodies, the fate of SARS-COV-2 virus in water /
113 wastewater bodies is yet to be elucidated (Nghiem et al., 2020). In addition, there is still a
114 substantial knowledge gap regarding to what extent the early detection of virus is possible, i.e.,
115 before the occurrence of widespread symptomatic cases, owing to the limitation in identification
116 techniques which mostly depend on the viral load in the patient's fecal matter. Furthermore, very
117 few authors have reported quantitative assessments to predict the loading of virus in wastewater
118 and its correlation to the official case statistics, although these of course are also hugely variable
119 depending on testing rates and approach.

120 With a second wave of the pandemic occurring across most parts of the world, our focus
121 here is to highlight and draw attention towards the potential transmission of the SARS-COV-2
122 virus through wastewater. In this regard, to help society fill the knowledge gap, the major objective
123 of this critical review is to synthesize current knowledge on approaches for treating wastewater
124 contaminated with the virus so as to decrease COVID-19's transmission chances, and to support
125 prioritization of the further research needs and the current barriers to implementation of the various
126 treatment methodologies in developing countries. The methodology used for selecting the
127 appropriate recent manuscripts, based on the objective of this work, are discussed in detail. Further,
128 the potential transmission and detection of SARS-COV-2 virus in wastewater, along with the risks
129 of infection through droplets / aerosols contaminated with infectious viral particles, and the
130 quantitative detection methods are discussed in detail to present a clear picture of the current state
131 of knowledge to the readers. Finally, the various remedial approaches for wastewater treatment
132 such as decentralized wastewater treatment and different potential disinfectants for wastewater

133 treatment, are presented and their advantages and disadvantages discussed. In tropical countries
134 with abundantly available solar energy, a sustainable low-cost approach for wastewater treatment
135 is also highlighted. With increasing COVID-19 cases, uncertainty in transmission paths and less-
136 societal knowledge and awareness, our review aims to create awareness and draw the attention of
137 researchers and society towards the potential severity of virus transmission through wastewater
138 and its potential remedies.

139 **2. Methodology**

140 The articles for the present state of the art critical review were carefully selected by considering
141 the impact of the reported research and the quality of the journals, respectively. Identification of
142 published work assessing the potential spread of SARS-CoV-2 virus through wastewater and the
143 various strategies for wastewater treatment to effectively control viral spread was carried out
144 through systematic searches in the Google Scholar, Science Direct (Elsevier), Web of Science,
145 Pub Med and Scopus databases using appropriate keywords such as "SARS / SARS-CoV-2 virus
146 in wastewater", "secondary SARS-CoV-2 virus transmission", "advanced wastewater treatment
147 for virus spread control". Further searches were made using keywords such as "wastewater
148 treatment" and "SARS-CoV-2 virus" for identification of the most relevant literature (up to March
149 2021) on SARS-CoV-2 virus transmission through wastewater and various methods to control the
150 spread. To select the suitable literature from the so-collected manuscripts in the context to
151 wastewater treatment process exclusively to control the spread of SARS-CoV-2 virus, the
152 following key points were considered:

- 153 ➤ Inclusion of all studies that describe SARS / SARS-CoV-2 virus transmission by any kind
154 of water sources;

- 155 ➤ Inclusion of manuscripts that reported a mechanism of virus transmission in water /
156 wastewater;
- 157 ➤ Inclusion of manuscripts that report detection methods for SARS-CoV-2 virus in water /
158 wastewater;
- 159 ➤ Inclusion of work that reports on impact and severity of virus spread at the social-
160 community level;
- 161 ➤ Inclusion of articles that focus on potential treatment of water / wastewater for deactivating
162 viruses;
- 163 ➤ Inclusion of articles on sustainable treatment strategies for viral deactivation
- 164 ➤ Exclusion of manuscripts that are entirely based on primary transmission of SARS-CoV-2
165 virus;
- 166 ➤ Exclusion of studies which don't report quantitative outcomes or merely repeat existing
167 results (i.e., review articles).

168 The mapping of literature content and bifurcation of the selected studies were executed based on
169 the following criteria:

- 170 ➤ What specific virus identification approach in water / wastewater was adopted?
- 171 ➤ What is the transmission mode of the virus through the water / wastewater system?
- 172 ➤ Is there any specific technique implemented to monitor the growth and spread of virus in
173 the water / wastewater system? If so, what are the methods to deactivate the viruses in water
174 bodies?
- 175 ➤ What treatment parameters were adopted to deactivate the virus?
- 176 ➤ What are the sustainable approaches for treatment of wastewater?
- 177 ➤ What hinders implementation of the wastewater treatment method in low-income countries?

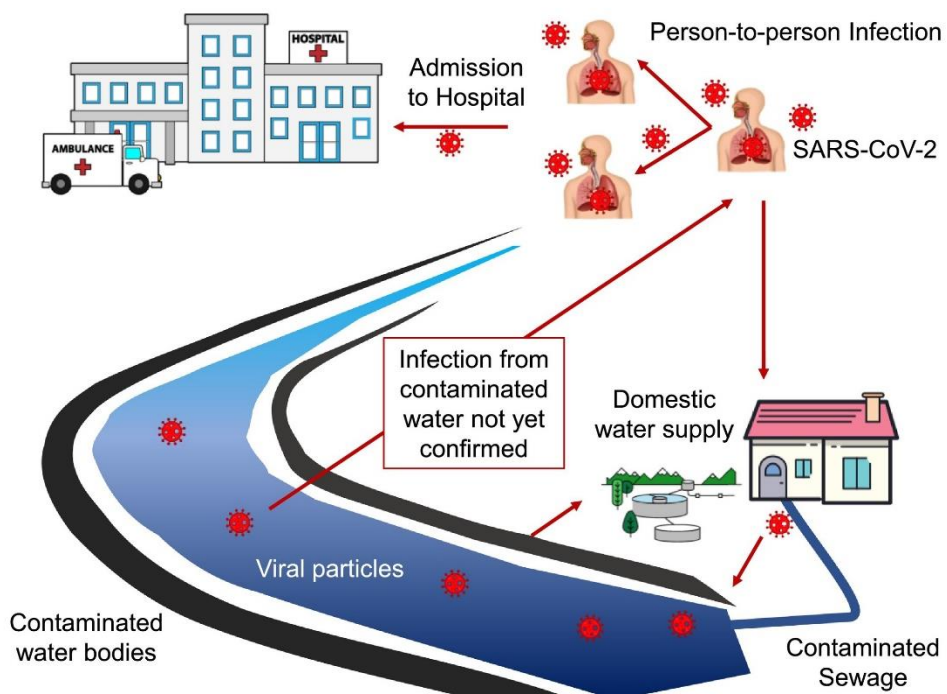
178 ➤ What specific conclusions are made regarding the effectiveness of the water treatment tactic
179 in controlling the spread of SARS-CoV-2 virus?

180 All the collected manuscripts were broadly classified based on the sources of virus secondary
181 transmission in water / wastewater and the individual wastewater treatment technologies were
182 further segregated depending upon the nature of treatment (decentralized, physical methods
183 including membrane technology and sedimentation approaches, solar assisted wastewater
184 disinfection, ozonation, chemical based disinfectants and biological based treatment including
185 algae) and its effectiveness for virus deactivation. Under each category, the different virus
186 deactivation approaches and the advanced techniques implemented for deactivating the virus
187 spread are organized and discussed in detail.

188 **3. Potential transmission and detection of COVID-19 virus in wastewater**

189 SARS-COV-2 RNA can enter wastewater systems via various pathways, as shown in Fig. 2
190 which highlights the virus's potential transmission pathways. These include discharged wastewater
191 from isolation or quarantine centers, and hospitals. Urine, stool, and feces related contamination
192 are the most common means of spreading contamination through wastewater systems. It was
193 reported that nearly 67 % of the stool samples of infected people tested positive for COVID-19
194 RNA, with counts reaching almost as high as those in sputum (10^9 copies/mL in sputum versus
195 10^8 copies/mL in stool) (Chen et al., 2020). It is also interesting that SARS-COV-2 RNA is
196 commonly found in stool even after the respiratory infection has resolved and, in some cases, even
197 after the respiratory samples are found negative (Xiao et al., 2020). Recently, a compartmental
198 epidemic logical model using the data from Wuhan, China, showed that the fecal-oral path is
199 significant in spreading the virus (Danchin et al., 2020), which is indicative of poor hand-washing,
200 often associated with water scarcity and/or lack of access to clean water (Hannah et al., 2020). The

201 Danchin study revealed that virus replication in the gastrointestinal tract is highly possible
202 (Danchin et al., 2020). Therefore, contaminated wastewater can be supposed to carry a substantial
203 amount of infective virus. Moreover, surface waters such as lakes and streams, where
204 contaminated wastewater is often directly released without appropriate treatment in low-income
205 countries, can also be a possible carrier for the SARS-COV-2 through the water-channel into
206 different parts of society. Likewise, groundwater resources are also not safe, as there might be viral
207 contamination through groundwater recharge. Fig. 2 shows the different pathways for
208 SARS-CoV-2 transmission through water systems. Furthermore, if the wastes from hospitals and
209 isolation wards are disposed without suitable treatment into the water bodies, this may lead to
210 disease transmission. Hence, safeguarding the water systems is highly essential to inhibit
211 unpredictable yet preventable contamination of available water resources from SARS-COV-2 and
212 other microorganisms.



214 Fig. 2. Sources and pathways of SARS-CoV-2 in water systems (Adelodun et al., 2020). Copyright
215 2020 Elsevier.

216 Detection of SARS-COV-2 in wastewater is highly challenging and presently different
217 approaches such as quantitative molecular methods and *in vitro* counts by the number of plaque-
218 forming units (PFU) are used to detect and monitor viruses. The PFU method provides a
219 measurable assessment of the infectious viral-particle load; however, it is difficult and slow owing
220 to the requirement for a suitable host for *in vitro* cultivation (Wigginton et al., 2015; Madigan et
221 al., 2012). Molecular methods show the ability to estimate (the COVID-19) viral RNA in
222 wastewater samples, but this method doesn't measure viral infectivity (Wigginton et al., 2015). It
223 is also important to understand that the viral identification sensitivity could be limited further by
224 the cytotoxicity of co-contaminants usually seen in wastewater samples. Moreover, virus
225 concentrations in wastewater samples need to be high compared to the RNA detection limit ($>10^6$
226 copies/mL) in order to distinguish infectious viral particles. Generally, real-time reverse
227 transcription polymerase chain reaction (RT-PCR) is considered the gold standard for determining
228 SARS-CoV-2 using a direct assay of human extraction, where the samples are collected from the
229 upper respiratory system using swabs. In real-time RT-PCR, the limit of detection is ~ 100 copies
230 of viral RNA/mL of the transport medium; however, the RNA detection limit is $>10^6$ copies/mL
231 in the case of wastewater. Therefore, the wastewater measurement method needs to be more
232 accurate with higher sensitivity for detecting the virus than that needed for clinical samples
233 detection. In order to achieve this, intact virions are concentrated on a cell-free substrate coated
234 with the analogous receptors after the enzyme treatment to eliminate the broken virions. Later, the
235 bound virions are amplified and measured by reverse transcription-quantitative polymerase chain

236 reaction (RT-qPCR). This method was used in recent studies to identify the SARS-COV-2 in water
 237 samples (Medema et al., 2020).

238 Table 1. Recent studies assessing the presence of SARS-CoV-2 in wastewater samples

Reference	Region of study	Genes analyzed	Outcomes
Kumar et al. (2020)	Ahmedabad, India	ORF1ab, N and S	2/2 influent water samples - Positive 2/2 effluent water samples - Negative
Sherchan et al. (2020)	Louisiana, USA	N1 and N2	2/15 raw wastewater samples - Positive All effluent water samples - Negative
Randazzo et al. (2020)	Valencia, Spain	N1, N2 and N3	35 /42 influent water samples - Positive 2/18 secondary treated water samples - Positive 0/12 tertiary effluent water samples - Positive
Nemudryi et al. (2020)	Bozeman, Montana, USA	N1 and N2	7/7 samples - Positive in March/April 2020
Wu et al. (2020)	Massachusetts, USA Istanbul, Turkey	N1, N2 and N3 RdRp	10/10 raw wastewater samples - Positive 9/9 sludge samples – Positive
Haramoto et al. (2020)	Yamanashi Prefecture, Japan	N1 and N2	0/5 influent samples – Positive 1/5 secondary effluent samples – Positive 0/3 river water samples – Positive

239

240 Table 1 presents the recently conducted studies on detection of SARS-CoV-2 in different
 241 wastewater samples globally through different targeted genes like ORF1ab, N1, N2, and N3 using
 242 RT-qPCR. Very few studies reported on whether the genetic material was present in free nucleic
 243 acids or in intact virus particles. It was seen that the majority of the samples tested at multiple

244 different locations globally (per 100,000 people) had demonstrated the presence of SARS-CoV-2
245 in untreated wastewater through RT-qPCR. Although RT-qPCR shows good outcomes in detecting
246 SARS-CoV-2 in wastewater, other methods must be developed in order to accurately determine
247 the infection in wastewater samples even under low virus load concentration. Presently, the
248 minimal infectious dose (MID) of the COVID-19 virus is unknown for humans (Kitajima et al.,
249 2020). However, this novel virus's rapid transmission shows that its MID is lower than or identical
250 to those of other enveloped viruses (Watanabe et al., 2020; Lindsley et al., 2020).

251 It is interesting to note that a range of factors affects the virions of SARS-COV-2 in
252 water bodies such as organic content, water temperature, and water pH. The survival time of the
253 SARS-COV-2 is estimated from the time needed for 90 % inactivation (T90) (Bogler et al., 2020).
254 Under different environmental conditions, the virus can remain infective for many days. However,
255 the method through which the virus translates into severe infection risk is still unknown, especially
256 as human activities on, and exposure to, water varies across seasons and regions. Lower
257 temperatures support longer persistence of SARS-CoVs infectivity; at 4 °C it has been shown to
258 remain infective for 14 days in wastewater whereas it remained viable for only two days at 25 °C
259 (Wang et al., 2020). Therefore, lower ambient temperatures under cold climatic conditions support
260 a higher survival of the SARS-COV-2. In view of the possible transmission of the SARS-COV-2
261 through water and wastewater, precautionary measures must be taken to manage wastewater
262 effectively. During winter or cold climatic conditions, hospitals located in the middle/high
263 latitudes can increase the wastewater treatment temperature by between 20 °C to 25 °C to reliably
264 and rapidly inactivate the SARS-COV-2.

265 **4. Risk of infection through droplets / aerosols contaminated with infectious particles and**
266 **its quantitative analysis**

267 With increasing threat of secondary transmission, the major exposure risk is associated with
268 the wastewater treatment plant worker, who can be directly exposed to the sewage through faults
269 or leaks in plumbing or sewer networks. In addition, water treatment workers could also be prone
270 to inhaling aerosols / droplets which are contaminated with the infectious viral-particles and there
271 is very high chance of such cases. Gholipour et al. (2021) examined and reported the detection of
272 Covid-19 virus RNA in about 40% of the air samples (6/15) of wastewater treatment plants, when
273 the prevalence of SARS-CoV-2 virus was very high in the region. Covid-19 virus RNA was
274 identified in the range of 5 to 188 genomic copies / liter of air and the maximum concentration
275 was investigated at the wastewater pumping station. However, very few occupationally exposed
276 cases of this indirect transmission risk through the wastewater aerosols / droplet have been studied
277 or reported as yet, and thus there is a lack of knowledge and reported literature regarding this kind
278 of possible infection. In view of societal equality and generalized safety, it is very important to
279 safeguard wastewater plants workers, who played a pivotal role for society during the lockdown.
280 Various factors affect the probability of infections arising in wastewater plant workers through the
281 inhalation of aerosols which are contaminated with corona virus, as follows:

282 ❖ **Climatic conditions:** Wind velocity and its direction along with turbulence and deposition are
283 the major factors which determine the transmission of virus through aerosols. These factors
284 can critically impact the generated aerosols height and the distance covered before they settle.
285 It is also expected that high wind velocity may lead to enhanced exposure of aerosols to the
286 populations living downwind of wastewater plants.

287 ❖ **Volume of the infectious viral-particles inhaled:** Volume of lung, inhalation rate and viral
288 particle size and density are crucial factor in view of infection likelihood (Wilkinson et al.,
289 2012). Generally, males have bigger nasal-cavities and higher, longer and narrower nasal floors

290 than females with similar body size (García-Martínez et al., 2016). This could result in males
291 breathing a higher volume of infectious viral-particles than female workers, which could result
292 in greater risk of contracting the SARS-COV-2 virus infection.

293 ❖ **Health response of workers:** The most critical factor for assessing the potential for infection
294 of the workers are the host response to the inhaled particles. With the available data, critical
295 infections of SARS-COV-2 virus are predominantly seen in patients with underlying health
296 conditions such as chronic-lung disease, diabetics, and cardiovascular disease (Bonow et al.,
297 2020). Previous studies of health effects in wastewater treatment workers have shown
298 enhanced prevalence of cardiovascular and breathing related conditions compared to control
299 populations (Albatany et al., 2011). Nevertheless, healthy persons are also infected by
300 particle exposure and therefore, all wastewater plants workers regardless of their health
301 conditions are at risk of infection, especially during severe outbreaks where viral loading may
302 be very elevated.

303 **4.1 Quantitative analysis:** Aerosols emitted from wastewater plants possess higher risk and
304 therefore, must be assessed. A human-fecal shedding technique was used for determination of the
305 concentration of SARS-CoV-2 in wastewater (Barker, 2014; Zaneti et al. 2021).

306 **Exposure assessment** – The aerosols generated in aeration tanks and pumping stations are
307 predominantly of diameter $\leq 10 \mu\text{m}$, which are considered to be respirable and could deposit in the
308 respiratory tract and reach the alveolar region of the lungs (USEPA, 2011).

309 The daily dose (dd, TCID₅₀ / day) of SARS-COV-2 aerosols inhaled by the wastewater treatment
310 workers can be calculated using an equation developed by (Barker, 2014) for other airborne
311 microbes:

$$312 \quad dd = C_c \cdot PC_{w-ar} \cdot AIR \cdot t_{exp} \cdot ARR \quad (1)$$

313 where, C_c is the SARS-COV-2 concentration in wastewater (TCID₅₀ / L), PC_{w-ar} is the microbial
 314 ‘water to air’ partitioning coefficient (L / m³), AIR is the average rate of inhalation (m³ / h), t_{exp} is
 315 everyday exposure time (8 h for professional exposure), and ARR is the retention rate of aerosol in
 316 lungs, determined using the following equation (Schoen et al., 2011):

$$317 \quad ARR = FF_i^1 \cdot FF_i^2 \quad (2)$$

318 where, FF_i^1 is the fraction of aerosols with size range of ‘i’ and FF_i^2 is the fraction of size range i
 319 which were deposited onto the lower respiratory tract.

320 The virus concentration in wastewater is determined using the following equation (Barker, 2014).

$$321 \quad C_c = \frac{C_i \cdot PR_{fs} \cdot S_d \cdot S_r \cdot FP}{dt \cdot Q_f \cdot CF \cdot 1000} \quad (3)$$

322 where, C_i is the cumulative number of COVID-19 cases, PR_{fs} is the % of people with fecal-
 323 shedding of SARS-COV-2. S_r and S_d are the shedding rate (copy / gram) and shedding duration
 324 (d) of SARS-COV-2 in the feces of patients, respectively, FP is the everyday production of fecal
 325 matter by patients (gram feces / person / day), dt is the time period of study, Q_f is the flow-rate of
 326 wastewater in the plant and CF is the conversion factor of genomic copy number to TCID₅₀. When
 327 determining viral concentration through quantitative analysis, care must be taken to account for
 328 uncertainty and variability inherent in the biological systems as suitable for the investigated
 329 conditions.

330 **5. Potential wastewater treatment options for COVID-19 inactivation**

331 Different precautionary measures have been suggested by the WHO to effectively control
 332 the spread of COVID-19, such as face masking at indoor and outdoor gatherings, social distancing,
 333 and frequent hand washing with alcohol-based sanitizer or soap. Although the precautionary

334 measures are effective in controlling the transmission, the fear of potential community
335 transmission is very high, particularly in the countries with lower income where several families
336 share (often limited) water systems and sanitation facilities. Hence, extensive measures are needed
337 to effectively control the spread from wastewater through effective treatment techniques. These
338 treatment approaches include physical, chemical and biological treatment methods, which are
339 focused on removal of suspended solids and bio-degradable organics (Crini et al., 2019, (Fu et al.,
340 2010). The efficiency of pathogen removal from water-treatment processes is characterized by the
341 Log Reduction Value (LRV), expressed as the relative number of live-microbes removed from the
342 system through any removal procedure and is represented as:

$$343 \quad \text{Log Reduction} = \log_{10}(C_{mb}) - \log_{10}(C_{ma}) \quad (4)$$

344 where, C_{mb} and C_{ma} signify the viable microbe numbers before and after the treatment. Various
345 wastewater treatment processes and potential remedial approaches such as decentralized
346 wastewater treatment, sedimentation and membrane technology (physical treatment processes),
347 chemical and biological processes including microalgae based treatment techniques are discussed
348 in the following section.

349 **5.1 Decentralized wastewater treatment for preventing virus spread**

350 The COVID-19 pandemic has created huge stress on the availability of clean water for
351 maintaining hygiene and contaminated wastewater treatment in order to safeguard communities
352 and reduce exposure. In general, the dedicated COVID-19 isolation wards and health centers to
353 monitor and treat the patients share the same sewerage systems with nearby societies. People living
354 in the same society are likely to use common water resources, especially in low-income countries,
355 and they may potentially be exposed to the SARS-COV-2 virus through shared water resources.

356 Furthermore, the inappropriate dumping of wastewater from hospitals without any treatment or
357 disinfection approach may cause community health risks and may spread the infection. As there is
358 a potential for the SARS-COV-2 virus spread in a centralized wastewater treatment systems, the
359 decentralized wastewater treatment strategies with affordable and low maintenance cost could play
360 a significant role (Matto and Singhal, 2020) during COVID-19. Design and development of small-
361 scale wastewater treatment plants can be viable alternatives to the centralized treatment plants in
362 COVID hotspots, such as isolation wards and quarantine centers, which are a high potential source
363 for spreading the virus through wastewater. In a decentralized treatment system, utilization of UV
364 radiation and some promising ecofriendly virucidal alternatives, such as performic acid, peracetic
365 acid and sodium dichloro isocyanurate, appear to be effective in disinfecting the Covid-19 virus
366 and thus combatting any potential contamination through wastewater transmission. Decentralized
367 wastewater treatment facilities that consist of light emitting diode (LED) based UV could be highly
368 useful (Naddeo and Liu, 2020). In low-income countries, where the infrastructure is not good, and
369 construction of a complete wastewater treatment plant is not possible in a short time span, the
370 usage of mobile wastewater treatment services with disinfection devices could be a better and more
371 feasible option. Rural solar toilets can also be a viable alternative as they can easily achieve water
372 temperatures up to 44 °C, which helps in the removal of pathogens (Moe and Izurieta, 2003).
373 Additionally, sanitary landfills/wetlands or ponds are also an effective method of discharging the
374 wastewater, and they can be treated with economic disinfectants like sodium hypochlorite. It has
375 been inferred from the above discussion that a cost effective method for controlling the viral spread
376 can be achieved through decentralized treatment of wastewater, and various dimensions should be
377 taken into consideration while designing this system, particularly the local issues related to the
378 suitability and availability while selecting this technology.

379 **5.2 Prevention of virus spread through wastewater by utilizing membrane technology**

380 Membrane filtration technology is considered to be a robust, non-invasive and non-toxic
381 technique. It is highly preferred for removing virus and considered as the most advanced method
382 for wastewater treatment. In this technology, ultrafiltration (UF) is an effective method for
383 removing viruses, macromolecules, pyrogens, and bacteria. UF utilizes membranes with 1000 kilo-
384 Dalton molecular weight cut-off that are explicitly designed to retain viruses, and usually more
385 than 4 logs of virus removal are attained while safeguarding good protein permeability. In
386 filtration, viruses of size less than the pore-size are carried with the fluid and pass through the
387 pores of membranes, while if the size of the pore is less than that of the virus, the virus get retained.
388 Size exclusion is the key mechanism of clearance by filtration. UF has potential to provide a
389 complete barrier to COVID-19 virus spread, as it can easily remove the virus whose diameter is
390 100 nm.

391 Filtration capability can be further enhanced using different surface characteristics of the
392 filtration membrane such as hydrophobic and charged regions which attract groups on the viral
393 envelope, leading to the removal of sizes beyond exclusion owing to the electrostatic and
394 hydrophobic interactions (Chaudhry et al., 2015; Bodzek et al., 2019). The usage of UF membranes
395 in bioreactors has further improved the virus removal capability through the combination of three
396 distinct mechanisms: steric removal, adsorption, and inactivation during treatment (Bodzek et al.,
397 2019). Owing to the advanced features of UF membrane in bioreactors, they removed
398 bacteriophage MS2 (virus) with high efficiency (4–7 log). Moreover, nano-filtration (pore size <
399 2 nm) with high pressure, using a tight and dense membrane system along with forward and reverse
400 osmosis membranes, can completely remove SARS-CoVs (Pendergast et al., 2011). These
401 filtration technologies are most efficient when used in tangential flow or cross flow mode, and are

402 being exploited in various virus removal and wastewater purification processes as they are cheaper
403 than other methods such as chromatography and also easier to implement. Nano-filtration
404 possesses features for separating the COVID-19 virus from wastewater, however extensive
405 experimental studies are needed prior to design and execution especially for wastewater
406 applications. Various effective experimental methods for predicting flux exist, but still there is a
407 lack of theoretical studies, predominantly those targeting the calculation of filtration efficiency
408 related to log reduction value, and hence, filtration efficiency should be considered for advanced
409 design and efficient operation of UF in terms of virus separation.

410 In addition to filtration, sedimentation is also reported to remove viruses (Verbyla et al.,
411 2105; Shin et al., 2015). Viral adsorption onto large-size settleable solids followed by
412 sedimentation is considered to be the main removal mechanism in many treatment plants (Verbyla
413 et al., 2105). The terminal velocity (V) of the dispersed solid settling due to gravity is represented
414 by the following equation:

$$415 \quad V = \sqrt{\frac{4 \cdot D \cdot g (\rho_p - \rho_w)}{3 \cdot C_D \cdot \rho_w}} \quad (5)$$

416 where D is diameter of the solid particle (m), g is acceleration due to gravity (m / s), ρ_p is the
417 density of the solid particle (kg / m^3), ρ_w is density of water (kg / m^3), and C_D is the drag coefficient.
418 Drag coefficient is calculated using the Reynolds's number (Re), which is expressed as:

$$419 \quad Re = \frac{D \cdot \rho_w \cdot u}{\mu} \quad (6)$$

420 where μ denotes the viscosity of water and u denotes the relative velocity, respectively.

421 It can be seen from these equations that increased settling velocity will be achieved by increasing
422 the diameter or volume of the particles (Mohammed et al., 2013) and similar concepts have been
423 used for removal of viruses in wastewater. As the virus attaches to the suspended-solids, the
424 combined agglomerated particles exhibit a larger size diameter with greater density, which in turn
425 leads to enhanced sedimentation and consequently to removal of the virus. LRV of 0.65-2.85 were
426 achieved for eleven different viruses during conventional activated sludge processes and similarly,
427 LRVs of 1.4–1.7 were achieved for noroviruses, rotaviruses and enteroviruses (Kitajima et al.,
428 2014; Zhou et al., 2015). Therefore, sedimentation is the main mechanism to reduce the viral
429 concentration in wastewater. However, only selected strains of rotavirus and norovirus were
430 removed by this process (Da Silva et al., 2008) and hence, further studies are required to make this
431 technology more effective and to assess its suitability for removal of the COVID-19 virus from
432 wastewater.

433 **5.3 Potential disinfectant strategies for prevention of virus spread**

434 **5.3.1 Solar assisted wastewater disinfection**

435 Solar assisted wastewater disinfection is a highly feasible and applicable option in several
436 types of aquatic environments (Nelson et al., 2018). Solar based drinking water disinfection is a
437 sustainable approach for disinfecting water, and it is widely promoted (Thakur et al., 2021a;
438 Thakur et al., 2021b; Thakur et al., 2021c; Thakur et al., 2020a; Thakur et al., 2020b; Thakur et
439 al., 2021d; Thakur et al., 2018a; Thakur et al., 2018b; Kumar et al., 2017). It mainly depends on
440 the intensity of solar radiation, the optical, physical, and chemical properties of the wastewater,
441 and the type of virus (Verbyla et al., 2015). Solar energy has abundant availability with yearly
442 solar irradiance higher than 2000 kWh/m²/y in most places on earth except Russia, Canada, Japan,
443 and South Korea. Tropical countries like India have plenty of sunshine, and average daily solar

444 radiation varies between 4-7 kWh/m² for different parts of the country. With an average of 250-
445 300 clear sunny days in a year, India receives about 5000 TWh of solar insolation per year, and it
446 shows excellent potential for solar assisted wastewater disinfection facilities. Various mechanisms
447 are used for the disinfection of wastewater by solar radiation such as the direct mechanism, which
448 needs photon absorption directly by the virus or an endogenous component such as proteins,
449 nucleic acids and other biomolecules. They absorb the UV-B fraction of solar radiation that leads
450 to structural change and thus, inactivates the virus. Recently, Sagripanti et al. (2020) examined
451 and explored the role of virus inactivation by the UV-B in sunlight in various populated cities
452 across the world. The results showed comparatively faster inactivation of COVID-19 virus (than
453 influenza A) during the summer time, demonstrating the important role of solar radiation on its
454 occurrence and spread. The authors concluded that more than 90% of COVID-19 virus was
455 inactivated by exposure to mid-day solar radiation after 11-34 min in the majority of US cities and
456 world cities during their respective summer. Ratnesar-Shumate et al. (2020) explored the role of
457 simulated solar radiation on the survival of COVID-19 virus dispersed in simulated saliva or
458 culture medium (Vero cells 'ATCC CCL-81' cultured at 37°C and under 5% CO₂ in complete
459 growth medium 'gMEM'). A solar simulator was designed to produce natural sunlight, specifically
460 in the range of ultraviolet. It was observed that solar radiation had a direct effect on survival of the
461 virus with 90% of the infectious virus being inactivated in 6.8 min in simulated saliva under the
462 simulated conditions; however, for culture medium, the time taken was around 14.3 min. Under
463 all simulated conditions, the virus's inactivation rate was greater when dispersed in simulated
464 saliva than in the culture medium. Fisher et al. (2011) examined the role of simulated solar
465 radiation on the inactivation of a single-stranded RNA bacteriophage 'MS2' and a double-stranded
466 DNA bacteriophage 'PRD1' in clear water (no exogenous sensitizers). It was observed that UVA

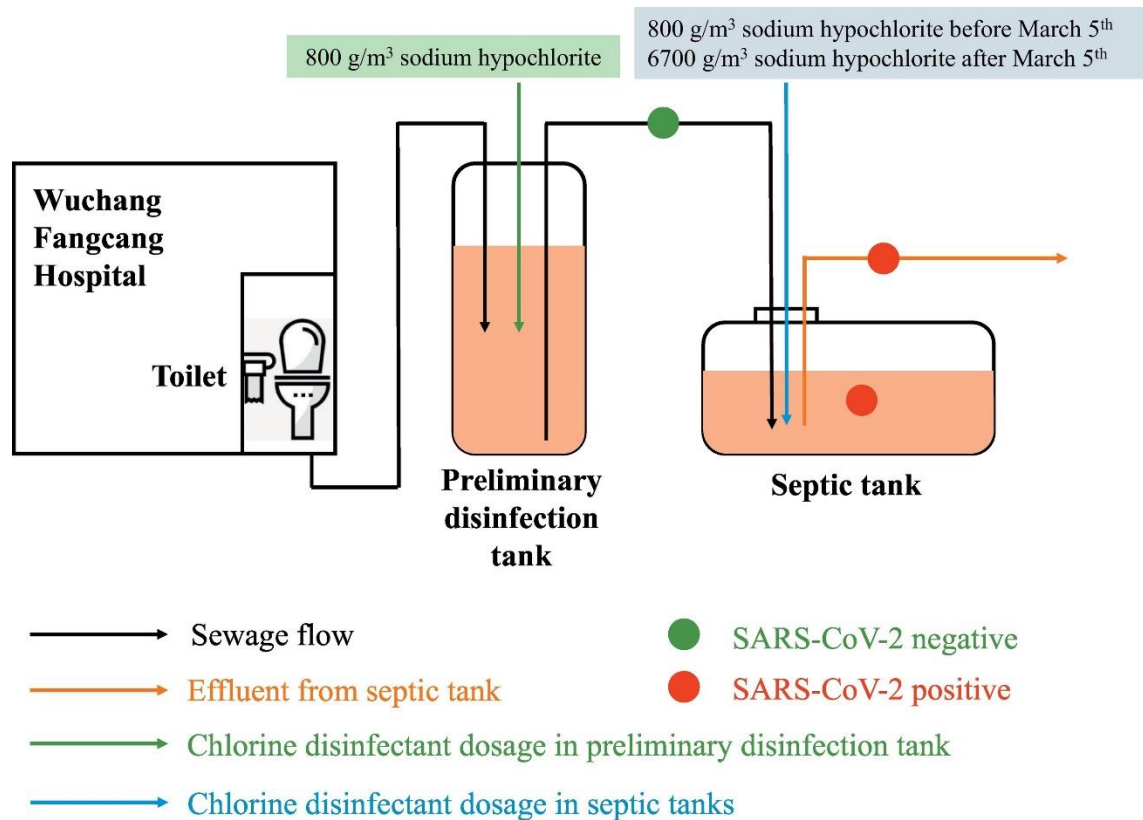
467 (320–400 nm) and UV-B (280–320 nm) could inactivate ‘PRD1’; however ‘MS2’ was inactivated
468 only by the UVB light. It is inferred from the above discussion that solar based disinfection is the
469 most sustainable way of wastewater treatment as well as being a cost-effective approach, which
470 has potential for treating contaminated water and deactivating the COVID-19 coronavirus.

471 **5.3.2 Ozonation for wastewater disinfection**

472 Ozone (O₃) is an oxidizing agent that can effectively inactivate viruses by oxidative
473 damage due to free radicals. As the viruses multiply only within their host cell, they transform host
474 cell protein into their own protein. O₃ inactivates the virus by diffusing through its protein coat
475 into the nucleic acid core, leading to the viral RNA damage. Once O₃ interacts with a virus, protein
476 is converted into protein hydroxides and protein hydroperoxides, resulting in the creation of
477 oxidative stress, against which viruses have no self-protection mechanisms. Recently, Tizaoui
478 (2020) proposed that usage of O₃ can be effective for SARS-CoV-2 virus as O₃ can disorder the
479 lipids and proteins of the virus's spikes. O₃ acts on the cytoplasmic membrane through breaking
480 the lipid molecules, thereby inactivating the virus (Kataki et al., 2020). In general, an initial dose
481 of O₃ (3–10 mg/L) with 10 min contact time demonstrates C_t values (the product of the
482 concentration of the disinfectant and the contact time with the water being disinfected) of 30-100
483 mg/min, which has been suggested is the requirement for successful ozonation (Paraskeva and
484 Graham 2002). Ozone is also considered as a significantly stronger disinfectant (10 times) than
485 chlorine in wastewater treatment (Hajjali et al., 2018). Even after dissolving in water, it did not
486 irritate skin, nor did it form a chemical film. It is a stronger disinfectant where the oxidation
487 reaction takes place several time faster than chlorine to inactivate viruses, bacterial and water-
488 borne pathogens. However, for wastewater treatment, ozonation's major issue is the increasing
489 acidity level in the treated water (Zaied et al., 2020) and it needs further investigation.

490 **5.3.3 Chemical based disinfectants for wastewater disinfection**

491 Chlorine-based disinfectants are widely used for water disinfection. Inactivation of
492 microorganisms by chlorine is mainly governed by various factors such as the oxidation of
493 sulfhydryl enzymes and amino acids, reduced nutrient uptake, loss of intracellular contents,
494 reduced oxygen uptake, inhibited protein synthesis, and decreased ATP production. Various
495 literature has shown the efficiency of chlorine towards the virus, but greater tolerance of the virus
496 can be seen for chlorine disinfectants (compared to ozonation or solar assisted disinfection) owing
497 to the absence of a metabolic enzyme system as compared to bacteria, which means that in viruses
498 there are less targets upon which the chlorine can act. Previous research revealed that 0.2 to 0.5
499 mg/L of free chlorine residual is sufficient to disinfect the SARS virus in municipal wastewater
500 (Wang et al., 2005). Engelbrecht et al. (1980) investigated the chlorine (0.1% available chlorine)
501 effectiveness against six enteric viruses and revealed a broader range of susceptibility of viruses
502 towards chlorine disinfection. pH is considered as the most important factor for achieving
503 inactivation of viruses in wastewater; the deactivation rate is greater at lower pH (6) than at higher
504 pH (10), yet also with a deviation in the relative sensitivity in respect of different viruses. pH is
505 the regulating factor which controls the dissociation of hypochlorous acid to the less microbicidal
506 form OCl^- . With increasing pH, transformation of undissociated hypochlorous acid to OCl^- takes
507 place and the disinfecting ability of Cl^- reduces. Therefore, at pH higher than 7, the time needed
508 to achieve the same degree of inactivation increases, requiring from 1.5-6 fold longer (Clarke et
509 al., 1956; Weidenkopf, 1958). Recently, Zhang et al. (2020) evaluated the existence of
510 SARS-CoV-2 RNA in septic tanks of Wuchang Cabin Hospital, and Fig. 3 shows the schematic
511 arrangement for the disinfection process of the septic tanks of hospital.



512

513 Fig. 3. Schematic illustration of the disinfection process occurring in septic tanks of the Wuchang
514 Cabin Hospital. Copyright 2020 Elsevier.

515 It was found that utilization of sodium hypochlorite for a contact period of 1.5 h at a dose of
516 800-6700 g/m³ effectively deactivated the SARS-CoV-2 in the hospital's septic tanks. It was also
517 suggested to revise the present WHO recommended disinfection scheme (freely available chlorine
518 ≥ 0.5 mg/L for at least 30 min) and the China Center for Disease Control and Prevention's current
519 guidance (freely available chlorine above 6.5 mg/L for 1.5 h) in order to completely remove the
520 COVID-19 viral RNA using a decentralized disinfection system. Kampf (2020) reported that usage
521 of sodium hypochlorite (0.21%) solution could be highly efficient for 4 log reduction of
522 COVID-19 in 1 min. Wang et al. (2005) illustrated that a free chlorine residual '0.2 to 0.5 mg/L'
523 in the municipal wastewater is enough to sterilize the SARS virus. Dellanno et al. (2009) showed

524 a reduction of 3 log in surrogate of the coronavirus mouse hepatitis virus (MHV) using 0.21%
525 sodium hypochlorite as a common disinfectant for a contact period of 30 s. Similarly, Ansaldi et
526 al. (2004) found that utilization of 0.05% hypochlorite solution can completely inactivate the
527 SARS-CoV with a contact time of < 1 min.

528 Quaternary ammonium-based compounds, being eco-friendly disinfectants, are also
529 recommended for wastewater treatment. For example, benzalkonium chloride (BKC), a quaternary
530 ammonium compound, can be an effective disinfectant for water treatment. The hydrophilic
531 cationic section of benzalkonium chloride generates electrostatic interfaces with a pathogen's
532 surface (negatively charged components), leading to the destabilization of the germs (McDonnell
533 and Russel, 1999). 1% benzalkonium chloride '1000 ppm' was used by Ansaldi et al. (2004) for
534 SARS-CoV, and outcomes showed that the virus lost viability after 30 min exposure. Rabenau et
535 al. (2005) revealed that BKC inactivated SARS-CoV under the limit of detection with a reduction
536 factor >4. However, owing to the restricted action of ammonium compounds with the viruses, it is
537 required to use it in combination with other disinfectants to achieve optimal results. WHO also
538 recommends peracetic acid (PAA) for virucide of SARS-CoV-2. It is reliable and possesses
539 excellent disinfectant characteristics with extensive anti-microbicidal activity (Antonelli et al.,
540 2013). Ansaldi et al. (2004) revealed that SARS-CoV-1 was disrupted using 35 ppm PAA with a
541 contact period of <2 min, while there was no effect after 30 min with the same concentration and
542 further investigation is thus needed. Although chemical-based disinfectants are preferred for
543 wastewater treatment, their role in the deactivation of SARS-CoV-2 is less explored. In addition,
544 optimization of the disinfectant concentration and their reduced efficiency in high organic loaded
545 wastewater needs to be further explored.

546 **5.4 Biological wastewater treatment**

547 Biological wastewater treatment techniques rely on microorganisms' (such as bacteria,
548 algae or fungi) cellular activity under aerobic / anaerobic conditions in order to achieve the
549 oxidation of the organic matter present in wastewater (Samer, 2015). Biological wastewater
550 treatment methods include membrane bio-reactors, activated sludge, bio-chemical systems,
551 biological contactors and anaerobic digesters. Since the majority of studies assessing the removal
552 of viruses have concentrated on membrane bio-reactors and granular reactors, these are described
553 in greater detail.

554 **5.4.1 Membrane bio-reactors:** These consist of a combined arrangement of membrane based
555 filtration with a suspended-growth biological reactor. This approach is a suitable alternative
556 method for achieving virus removal from wastewater owing to the excellent features like a reduced
557 ecological footprint and high effluent quality (Marti et al., 2011). The principal mechanism of
558 pathogenic bacteria removal is the process of size exclusion, whereas the mechanism of virus
559 removal is less studied and not fully understood. Sepehri et al. (2018) highlighted that membrane
560 fouling in membrane bio-reactors mainly depends on microbial cell density and their population
561 structure. The authors concluded that suitable organic carbon to nitrogen (C/N) loading ratio could
562 control the microbial population and benefit the nitrifiers, considerably mitigating the fouling.
563 Various studies have highlighted the role of mixed liquor suspended solids and backwashed
564 membranes in the inactivation of viruses (Xagorarakis et al., 2014; Miura et al., 2015). Da Silva et
565 al. (2007) determined an LRV for norovirus of 5.2–5.5 in a membrane bio-reactor. Similarly, LRVs
566 of 4.8, 6.3, and 6.8 were achieved in a membrane bio-reactor for noroviruses, adenoviruses, and
567 enteroviruses, respectively (Simmons et al., 2011). In contrast, Zhou et al. (2015) concluded that
568 complete removal of several viruses, including rotaviruses, noroviruses and enteroviruses could
569 not be achieved by this method. This discrepancy could be attributed to the fact that the membrane

570 bio-reactor method mainly focusses on physical removal of viruses, whereas the removal is greatly
571 governed by the virus structure, mixed liquor suspended solids, solids and hydraulic retention time
572 along with frequent cleaning of the membrane in order to achieve effective removal. In addition,
573 this method is energy intensive, has a high operational cost, and requires proper disposal of the
574 virus-contaminated sludge produced. The aforementioned drawbacks of this technology can be
575 overcome by utilizing microalgae-based process either alone or coupled with the membrane
576 technology to generate safe biologically treated water.

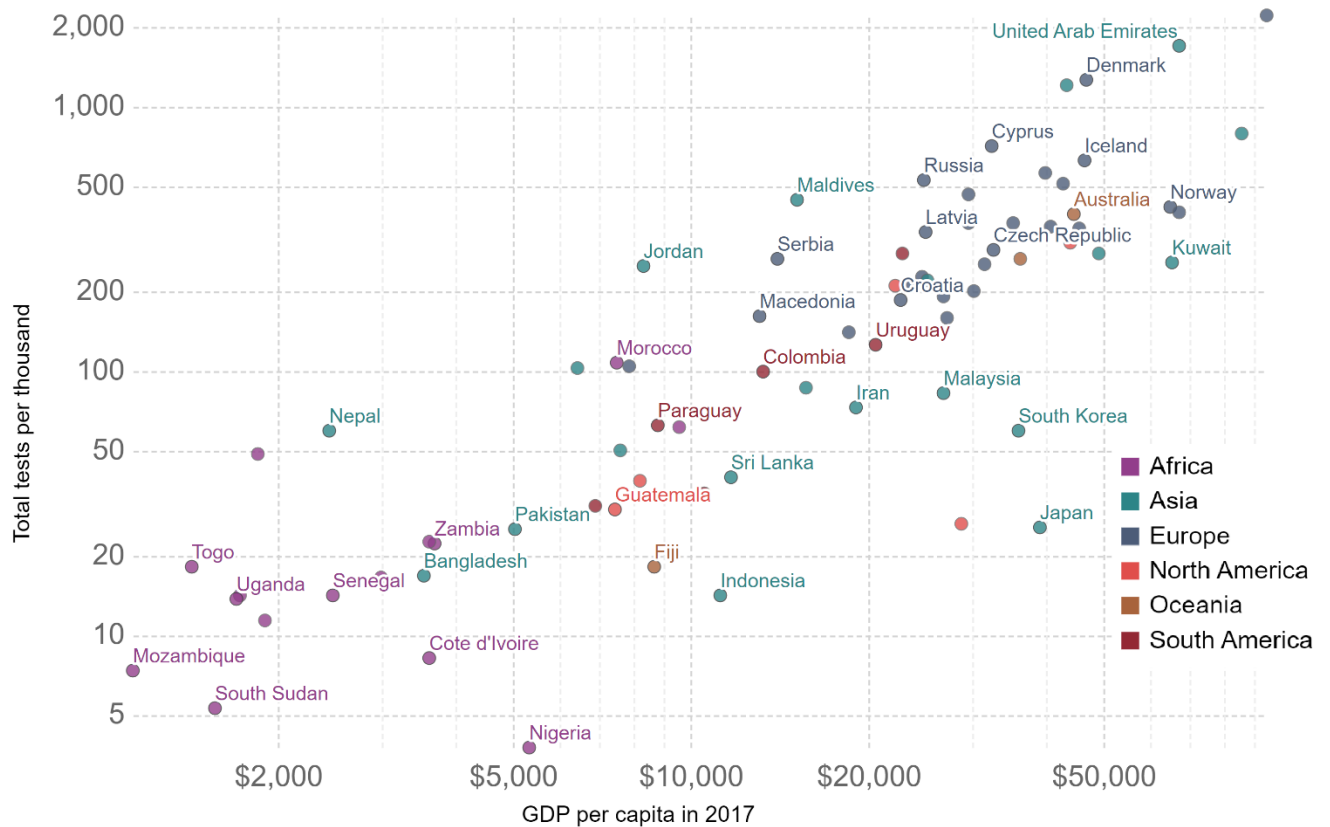
577 **5.4.2 Microalgae-based wastewater treatment:** The usage of macro / micro algae is gaining
578 enormous attention in removal of pollutants including viruses from wastewater in recent years
579 (Prajapati et al., 2014). Several researchers have studied the cultivation of microalgae in membrane
580 bio-reactors, oxidation ponds and biofilm reactors to estimate their efficacy for wastewater
581 disinfection. Recently, Delanka-Pedige et al. (2020) demonstrated that utilization of microalgae in
582 wastewater treatment through employment of extremophile *Galdieria sulphuraria* leads to high
583 removal rates of noroviruses (1.49 ± 0.16) and enteroviruses (1.05 ± 0.32). Scalable and
584 sustainable filter paper made from *Pithophora* cellulose were studied for drinking water
585 purification purposes. Results showed that all types of bacterial and infectious viruses were
586 successfully removed from sample water by this filter paper. Sepehri et al. (2020) demonstrated
587 that the aeration system in conventional nitrification processes can be substituted by a microalgae
588 based cleaning process which will result in less metabolite generation, improved carbon capture,
589 augmented nutrient removal, and decreased sludge production. Similarly, Sepehri et al. (2019)
590 found that a nitrification intensification strategy and nitrite-oxidizing bacterial enrichment using a
591 zero C/N ratio reduced microbial metabolites by 50% as compared to the conventional process and

592 improved the nitrification efficacy in the activated sludge involved process. This improved
593 efficiency should also lead to increased effectiveness of viral deactivation.

594 **5.5 Large scale community wise monitoring and testing of COVID-19 RNA in wastewater**

595 The countries with lower income, determined according to GDP per capita, have in general
596 conducted lower testing for COVID-19 compared to the developed nations, as shown in Fig. 4 (till
597 December 2nd 2020). There is presently a substantial gap in COVID-19 testing in various low-
598 income nations, with only 779,708 persons tested so far in Nigeria as of December 4, 2020, out of
599 about 200 million population, which is Africa's most populated country (NCDC, 2020).
600 Unfortunately, the transmission of the Covid-19 virus in these nations has been ascribed to the
601 incompetence of quickly detecting the infected people before the virus transmits to others and thus
602 spreads the COVID-19 virus (Mehtar et al., 2020). As the initial identification of the virus could
603 be made through faeces (Orive et al., 2020) rapid testing and monitoring of the virus in the
604 municipal/societal wastewater might be an effective technique to control the spread. This method
605 will be more suitable for low-income countries where the virus testing in communities is still
606 limited. Initial surveillance should be done for the pervasiveness of the COVID-19 infection in the
607 populace by observing the abundance of COVID-19 virus in wastewater, and then, the currently
608 applied inspection of symptomatic and/or likely exposed individuals should be carried out for
609 episodic analysis. Recently, Daughton (2020) emphasized the significance of large-scale
610 community wide testing as an economical method for monitoring the status and development of
611 COVID-19 infections. Moreover, improved water quality and adequate sanitation are also essential
612 to effectively prevent the unexpected spread of the COVID-19 and other potential human enteric
613 related viruses that might originate from an infected person's feces.

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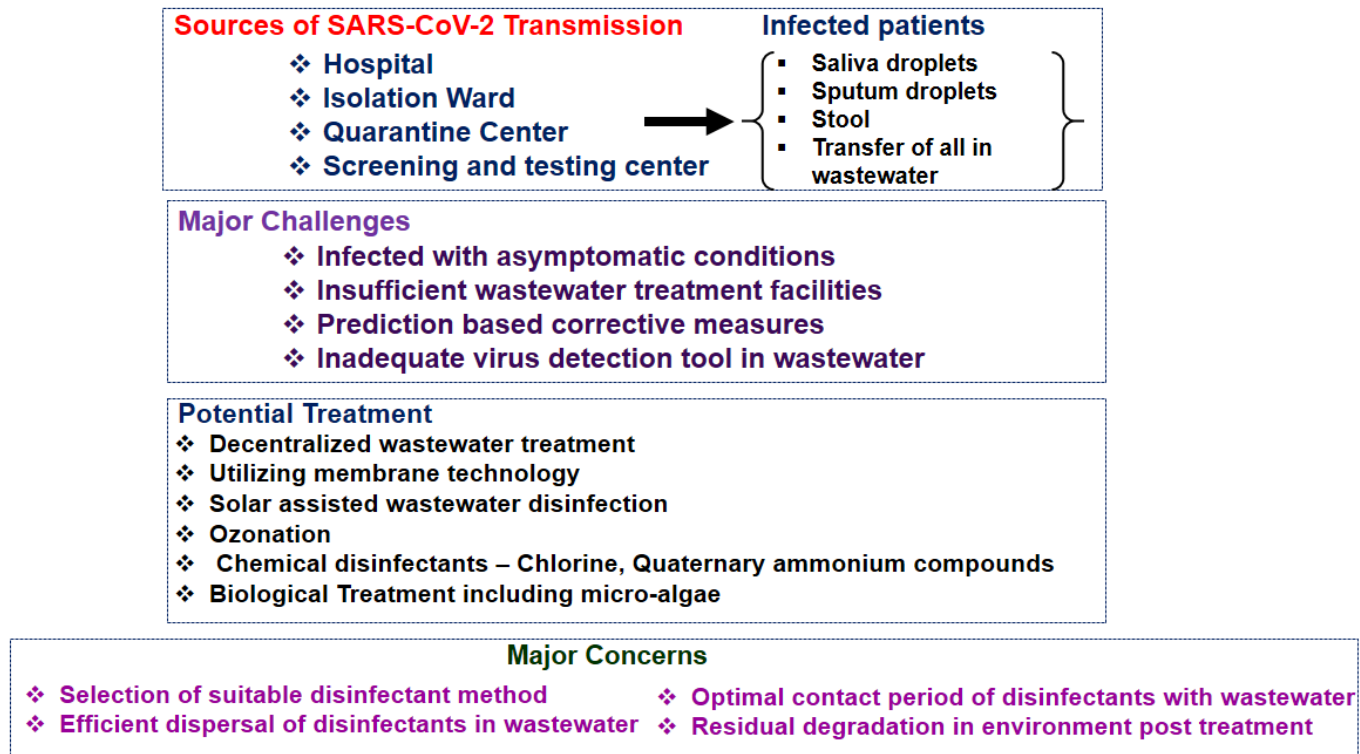
616 Fig. 4. Total COVID-19 tests per 1,000 population vs. GDP per capita (Our world in data, 2020)

617 **6. Viewpoint and conclusion**

618 The present effort of public health experts and medical professionals dealing with the COVID-
 619 19 pandemic is understandably focused on controlling its direct human-to-human spread and the
 620 care of infected individuals. Nevertheless, the potential spread of the virus through secondary
 621 transmission must not be underrated. Evidence for the existence of COVID-19 viral RNA in
 622 wastewater systems is seen globally, and the risks associated with waterborne transmission should
 623 be considered as severe. This needs to be quickly evaluated, especially in low-income countries
 624 where higher population density, poor sanitation infrastructure, lack of appropriate wastewater
 625 treatment facilities and direct exposure to aerosolized wastewater are major concerns, and may
 626 damage the hard-won achievements of the present control measures to reduce individual contacts,

627 leading to a huge spike in COVID-19 cases. Various studies have confirmed the existence of
628 viruses at sewage plants, however, there is no data related to the effectiveness of current
629 disinfection approaches as utilized on real wastewater in the treatment facilities against Covid-19.
630 Therefore, extensive research should be carried out urgently to identify the prevalence of SARS-
631 CoV-2 viral particles in wastewater in order to gain the crucial information related to the virus's
632 abundance in raw and treated wastewater, in order to (1) evaluate the effectiveness of existing
633 disinfection methods for inactivation of SARS-COV-2 and where additional disinfection regimes
634 are needed temporarily to deal with this new challenge; (2) ensure the reduction of potential
635 secondary exposures by appropriately treating wastewater, and ensuring effluents are virus-free;
636 and (3) facilitate monitoring and early-warning of potential hot-spots of infection, enabling local
637 preventative responses to be implemented in a timely manner. Further, the requirement for
638 disinfectants and application regimes should be evaluated according to the loading of the virus.
639 Thus, surveillance should be a core aspect of policymaking and wastewater treatment modalities
640 in order to effectively monitor and control the spread of SARS-CoV-2 infections in society.

641 To minimize human exposure to the Covid-19 virus via waterborne transmission, contaminated
642 wastewater from isolation wards, hospitals, testing centers, and quarantine centers should be
643 disinfected and treated correctly before being discharged into the main sewerage systems. In low-
644 income countries with inadequate centralized wastewater plants, decentralized wastewater
645 treatment with solar energy utilization can be incorporated to efficiently inactivate the virus
646 locally. Figure 5 presents a summary of the major considerations for determination of the optimal
647 treatment to implement locally depending on local conditions (e.g., UV availability, volume or
648 wastewater to be treated, current waste infrastructure capabilities etc.).



649

650 Fig. 5. Various potential wastewater treatment strategies and concerns during Covid-19
 651 pandemic.

652 In tropical countries like India, where there is abundant solar energy availability, a solar-based
 653 disinfectant solution can be a viable option for wastewater treatment. Simple wastewater
 654 treatments such as wetlands, ponds, or lagoons could be a superior choice for viral inactivation
 655 under the joint effect of solar radiation, comparatively long retention time, high pH, and microbial
 656 action. The usage of chemical disinfectants such as the widely available chlorine, sodium
 657 hypochlorite, benzalkonium chloride, peracetic acid etc. have shown potential in terms of virucidal
 658 properties. Biological treatments including microalgae can be a viable solution for viral removal
 659 from wastewater. Fig. 5 presents the different strategies towards the treatment of wastewater and
 660 some major concerns that must be considered during the selection of the most appropriate
 661 treatment in the view of the SARS-CoV-2 virus.

662 Nevertheless, further technical evidence is needed to confirm the effectiveness of viral
663 disinfection policies in wastewater, and the impact of different viral loadings on the treatment
664 efficiency. In conclusion, there is a pressing need for improved monitoring and risk assessment
665 along with the implementation of management policies for controlling the spread of COVID-19
666 via wastewater. To effectively control the spread of the novel coronavirus, policymakers should
667 emphasize systematic testing of the disinfectants' efficiency and concentration ranges under
668 different environmental conditions (e.g., different organic loadings, different water quality
669 scenarios, etc.). Beyond SARS-CoV-2 infections, these methods will also be helpful in improving
670 the identification, response, and inactivation of future viral disease outbreaks, and indeed in
671 controlling other enteric viruses responsible for diarrhea and other intestinal conditions.

672 **Declaration of Competing Interest**

673 The authors declare no conflicts of interest.

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