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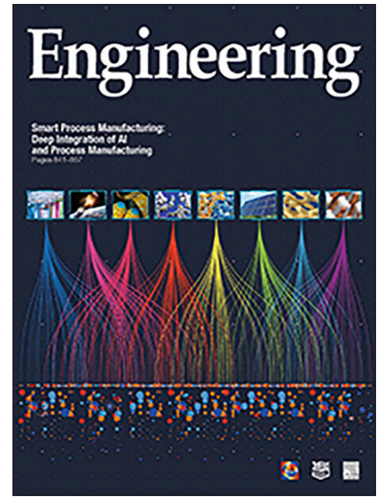

Enlightenment from the COVID-19 Pandemic: The Roles of Environmental Factors in Future Public Health Emergency Response

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Research

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Enlightenment from the COVID-19 Pandemic: The Roles of Environmental Factors in Future Public Health Emergency Response

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Abstract

The coronavirus disease 2019 (COVID-19) pandemic is challenging the current public health emergency response systems (PHERSs) of many countries. Although environmental factors, such as those influencing the survival of viruses and their transmission between species including humans, play important roles in PHERSs, little attention has been given to these factors. This study describes and elucidates the roles of environmental factors in future PHERSs. To improve countries' capability to respond to public health emergencies associated with viral infections such as the COVID-19 pandemic, a number of environmental factors should be considered before, during, and after the responses to such emergencies. More specifically, to prevent pandemic outbreaks, we should strengthen environmental and wildlife protection, conduct detailed viral surveillance in animals and hotspots, and improve early-warning systems. During the pandemic, we must study the impacts of environmental factors on viral behaviors, develop control measures to minimize secondary environmental risks, and conduct timely assessments of viral risks and secondary environmental effects with a view to reducing the impacts of the pandemic on human health and on ecosystems. After the pandemic, we should further strengthen surveillance for viruses and the prevention of viral spread, maintain control measures for minimizing secondary environmental risks, develop our capability to scientifically predict pandemics and resurgences, and prepare for the next unexpected resurgence. Meanwhile, we should restore the normal life and production of the public based on the "One Health" concept, that views global human and environmental health as inextricably linked. Our recommendations are essential for improving nations' capability to respond to global public health emergencies.

1. Introduction

The global outbreak of coronavirus disease 2019 (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the biggest crisis facing humanity since World War II. The number of cases has been increasing in many countries with over 75 million confirmed cases and over 1.6 million deaths around the world by December 21, 2020, at which time the number of cases is increasing exponentially in North America and Europe [1]. Surveillance of SARS-CoV-2 is expected to continue until 2024 in an attempt to predict the possible resurgence of COVID-19, even if the virus may be well controlled in the future [2]. The pandemic is challenging the current public health emergency response systems (PHERSs) of many countries. Although environmental research on viruses is an essential part of mid- and long-term priorities to control COVID-19, as proposed by "A Coordinated Global Research Roadmap" issued by the World Health Organization (WHO) (Fig. 1) [3,4], little attention has been given to the roles of environmental factors in PHERSs. Medical and public health researchers mainly focus on the pathogenesis of viruses, clinical management, prevention and control of infection, and development of therapeutics and vaccines, whereas environmental engineers and scientists are mainly concerned with understanding and predicting the transmission of viruses and their secondary environmental risks [5–7]. Hence, there is currently no proper integration of public health and environmental science in PHERSs.

Outbreaks of infectious diseases can be related to destruction of the environment, deterioration of ecosystems, extreme weather, and changes in other environmental factors [8]. Environmental factors such as temperature, humidity, and ultraviolet (UV) radiation are important for the continuous spread of SARS-CoV-2 around the world [9–11]. Furthermore, the environment is closely related to public health. For example, $PM_{2.5}$ (particulate matter with an aerodynamic diameter no greater than 2.5 μm) pollution impairs the cilia of the upper airways and weakens the human immune response, potentially leading to increased lethality of COVID-19 [12]. Thus, neglect of environmental factors will affect the prevention and control of viral pandemic diseases. To improve current PHERSs and proactively respond to public health emergencies, it is important to in

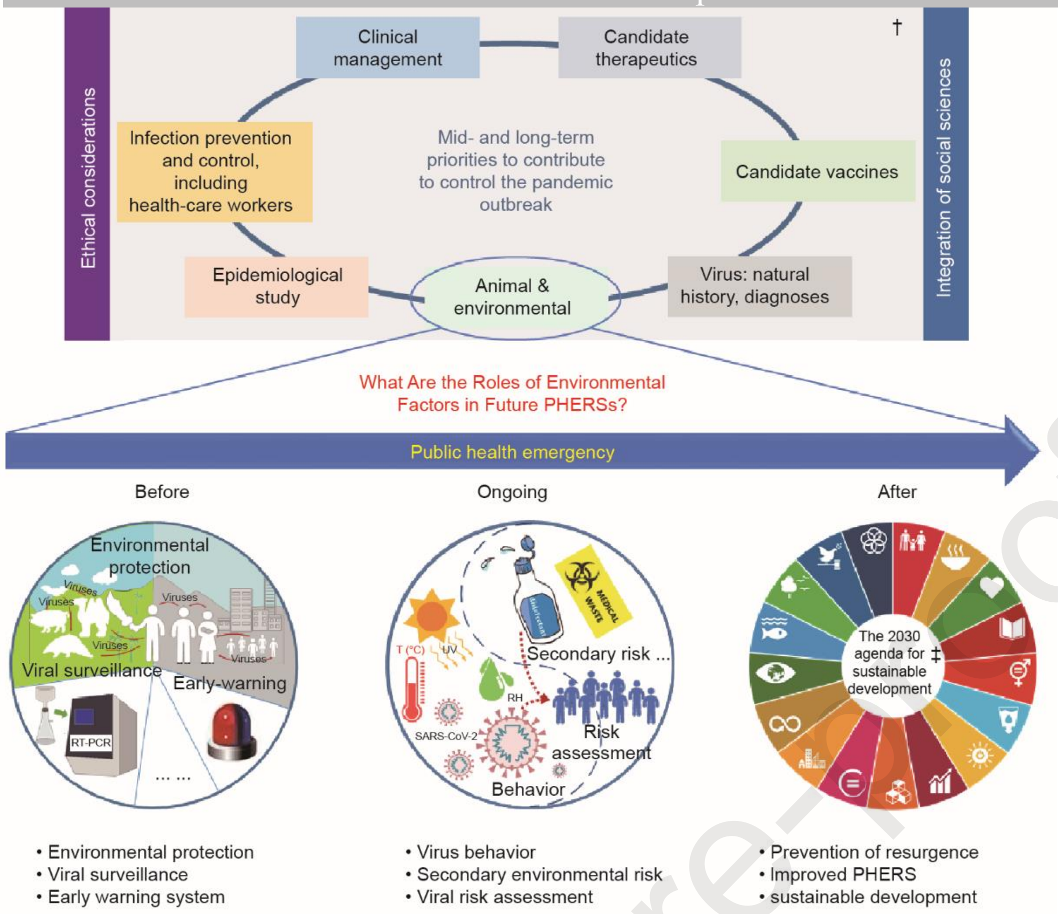

Fig. 1. An illustration of the roles of environmental factors in future PHERSs. Before a pandemic outbreak, environmental and wildlife protection should be strengthened, detailed viral surveillance should be conducted in animals and hotspots, and early-warning systems should be improved to minimize the outbreak of a pandemic. During a pandemic, the impacts of environmental factors on viral behaviors should be studied; also, control measures to minimize secondary environmental risks and timely assessments of viral risks and secondary environmental effects should be undertaken in order to reduce the impacts of the pandemic on human health and ecosystems. After a pandemic, surveillance for viruses and prevention of viral spread should be strengthened, control measures for minimizing secondary environmental risks should be maintained, and scientific prediction capability should be developed in order to respond to the next unexpected resurgence in a timely manner. Meanwhile, the normal life and production of the public should be sustainably restored. (Sources of illustrations: † reproduced from Ref. [3] with permission of WHO; ‡ the 17 goals are from Ref. [4]). T: temperature; RH: relative humidity.

China’s PHERS, established after the outbreak of severe acute respiratory syndrome (SARS) in 2003, involves systems for institutions, emergency management, medical treatment, control, and support, but ignores the influences and functions of environmental factors. The US PHERS emphasizes cross-departmental collaboration, among which the Department of Health and Human Services bears the primary responsibility for public health management, and the Environmental Protection Agency regulates the safety of air, water, and ecosystems [13]. However, the International Health Regulations that came into force in 2007 barely consider the influences of environmental factors [14]. Nonetheless, the Sendai Framework for Disaster Risk Reduction 2015–2030, which was adopted by the United Nations’ member nations in 2015, requires a more balanced approach in which countries consider social, environmental, political, and institutional factors in the responses to emerging infectious diseases [15]. For COVID-19, “A Coordinated Global Research Roadmap,” which was published in March 2020, emphasizes that additional studies of the sources, transmission, and stability of viruses in various environments will facilitate the prevention and control of pandemics in various regions [3]. Nevertheless, the integration of environmental factors into PHERSs remains an urgent problem.

Unlike organic and inorganic pollutants, viruses are alive and can be transmitted via human respiratory droplets, direct contact, and aerosols [16], facilitating rapid outbreaks of pandemics. To prevent and control outbreaks of viral pandemics and improve national capabilities to respond to public health emergencies, environmental factors should be integrated into PHERSs based on the “One Health” concept and on harmonious coexistence between humankind and the natural environment [17]. More specifically, the significance of environmental factors should be fully developed before, during, and after the response to public health emergencies (Fig. 1). Elaborated measures are described below.

2. How can pandemic outbreaks be prevented?

Frequent contact between humans and animals can increase the possibility of pandemic outbreaks (Fig. 2) [18]. To minimize the outbreak of a pandemic (i.e., prior to an outbreak), it is a prerequisite to enhance environmental and wildlife protection, such as the protection of natural habitats and minimization of wildlife poaching and trading (Fig. 1). Surveillance of viruses in the environment and in hotspots will provide useful information to develop more reliable early-warning systems (Fig. 1).

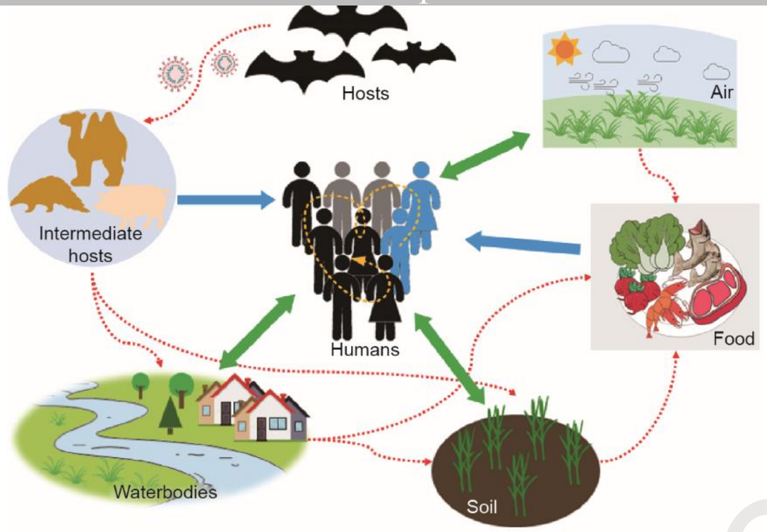

Fig 2. Possible virus transmission routes in the environment.

2.1 Protection of the environment and wildlife

2.1.1 Protection of wildlife habitats

Destruction of wildlife habitats forces wildlife and humans into closer and closer proximity, and hence increases the possibility of cross-species viral transmission [18,19]. Humans move into undeveloped areas through logging, hunting, roadbuilding, mining, agriculture, and animal farming—activities that fragment wildlife habitats and increase the contact between humans and wildlife [19]. Nowadays, the frequency of viruses "hopping" from animals to humans is two to three times greater than it was in the 1980s [18].

To reduce the cross-species transmission of viruses, it is recommended to protect forest resources [8]. To be specific, disorganized activities such as deforestation and mining should be restricted, and reforestation; the protection of natural forests, returning farmlands to forest, and the application of wood substitutes should be encouraged in order to increase forest coverage and protect biodiversity as a means of minimizing virus outbreaks. Although such measures might slow economic growth, they will promote sustainability and may have a high return in the long run.

2.1.2 Wildlife protection

Due to the huge demand for wildlife, wild animals such as bats, pangolins, and boars have been hunted, transported, and traded globally [20]. In addition, wildlife farming is industrialized in some countries. For example, wildlife farming industries in China involve about 15 million people and facilitate the spread of zoonotic diseases [21]. Wildlife markets bring various species into close proximity, and live and dead animals are maintained and sold with poor regulations and health screening [22], posing a serious threat to public health.

On 24 February 2020, China's National People's Congress adopted legislation to prohibit the illegal trade of wildlife and the consumption of field-harvested and captive-bred wildlife [23]. This policy was supported by scientists and by a number of international organizations (e.g., the Humane Society International and the WHO) [24,25]. However, banning the trade and consumption of wildlife as food for humans is not enough to protect people from zoonotic diseases. If wildlife markets were forced to close, the wildlife trade would go underground, which could increase the difficulty of managing it [26]. To manage wildlife markets and reduce the potential for virus transmission, the following measures are recommended:

(1) Facilitating the transformation and suppression of the wildlife farming industry by providing financial subsidies [27];

(2) Improving disease surveillance and implementing a system to manage animal farming industries by promoting handwashing, wearing personal protective equipment, enhancing disease surveillance, preventing the mixture of different animal species, limiting animal densities in captivity, and adopting veterinary care with high standards [26];

(3) Advancing the hygiene and regulatory standards of animal markets using similar measures as described in part (2), above [22];

(4) Limiting the global consumption of meat and shifting consumption toward plant-based foods [26];

(5) Stringently managing livestock and seafood from abroad by tracing their sources and strengthening health screening at points of import [19].

2.2 Surveillance of viruses in the environment

2.2.1 Surveillance of viruses in animals

To prevent pandemics, knowledge of viruses in the environment is essential (Fig. 2). Some programs have tried to discover viruses in wildlife and high-risk humans. For example, between 2011 and 2015, surveillance of viruses in bats from a cave in Southwest China found 11 kinds of novel coronaviruses [28]; furthermore, from 2009 to 2019, the PREDICT project, supported by the US Agency for International Development, found 949 emergent viruses in 164 000 humans and animals [29].

However, knowledge of novel viruses is still limited in comparison with the millions of yet-to-be-discovered viruses on the plan

een established in North America and Europe. In contrast, less studied regions such as Africa, Central and South America, and Southeast Asia are at high risk for viral transmission [30].

To better understand pathogens in wildlife and predict the next pandemic, governments should provide more funding to support research to screen viruses in high-risk animals and humans. More specifically, a surveillance system with lower cost and wider viral monitoring should be developed as soon as possible, and more laboratories should be established in high-risk regions [30]. Local scientists and workers in wildlife and healthcare could be trained to use accessible molecular equipment and conduct basic experiments with biosafety standards in order to screen viruses in wildlife and prevent the spillover of pathogens into humans. Compared with wildlife, the biosecurity of livestock and poultry can be controlled more easily. Livestock and poultry are intermediate hosts of pathogens, making viral surveillance necessary (Fig. 2). Although the surveillance of viruses in animals is onerous and expensive, this cost is small compared to the economic losses of a global pandemic [18].

2.2.2 Surveillance of viruses in hotspots

There are various transmission routes of viruses in the environment. As shown in Fig. 2, viruses are very likely to be transmitted via contaminated water, aerosols, soil, food packaging, and so forth, which are closely related to human wellbeing [31–33]. Animal surveillance combined with human testing programs can help identify infectious pathogens [34]. There are many zoonotic hotspots with a high risk of viral transmission, which gather a considerable number of viruses and promote the survival of viruses with dark, wet, and cold conditions. For example, wastewater is a source and pool of viruses, and threatens the health of sewage workers through direct contact or indirect bioaerosols [35]. In low-income areas, exposure to untreated wastewater and fecal wastes can increase the likelihood of viral transmission [34]. In rural areas of China, human feces and urine are often used to produce biogas and organic fertilizer, which can greatly elevate the risk of fecal–oral transmission of viruses in the community. Gathering places of live or dead livestock, poultry, seafood, and meats, such as farms, slaughter-houses, and wet markets, are hotspots for the cross-species transmission of viruses [19,22]. Due to the cold, wet, and dark conditions, the global cold-food supply chain has become a pathway for the transmission of viruses [36]. For example, it has been suggested that the recurrence of COVID-19 in Beijing, Tianjin, and Qingdao, China, might be the result of frozen seafood from abroad, which could have been contaminated during processing, transportation, or packaging [33,37].

To reduce the risk of viral transmission, it is recommended that routine environmental surveys should concentrate on the surveillance of viruses in zoonotic hotspots, such as the influents and effluents of wastewater treatment plants (WWTPs), village sewage discharge, sanitation infrastructures, farms, slaughter-houses, wet markets, and cold-food supply chains in order to provide sufficient evidence for early warning of public health emergencies. Nevertheless, standards for viral surveillance in hotspots are scarce. Commonly used indicators of pathogens in water quality monitoring are mainly fecal indicator bacteria and several enteroviruses [38], whereas the indicators for enveloped viruses are blank for routine monitoring purposes. Also, there are great differences between enteroviruses and enveloped viruses in terms of viral structures, stability, survivability, and pathogenicity. Appropriate indicators of viruses that react similarly to target infectious viruses should be selected by means of meta-viromics to determine the biosecurity of hotspots [38]. Detailed protocols for viral surveillance in hotspots should be established and adopted in routine monitoring in the near future.

2.3 Establishment of a shared platform and improvement of early-warning systems

Surveillance of viruses in the environment is difficult and requires collaboration among countries. Accordingly, the sharing of resources and information will be necessary. It is recommended to establish a shared biobank containing all viral information from animals and hotspots for better preparation for the next pandemic. The biobank could be managed by an organization following principles of transparency, ethics, equitable access, and respect for international laws [39], and partner countries could share data from the biobank at an affordable cost according to their contributions to the biobank establishment. Based on the knowledge of viruses in the biobank, scientists could assess the zoonotic risk of individual viruses using statistical and machine-learning approaches and could predict the most likely zones of viral outbreaks so as to improve the early-warning capabilities of PHERSs.

3. How can the impacts of pandemics be reduced?

To better control pandemic outbreaks (i.e., during the occurrence of a pandemic), increased attention should be given to the impacts of environmental factors on the behaviors of viruses (Fig. 1). Secondary environmental risks produced during a pandemic response should be controlled to minimize the impacts of the pandemic on ecosystems and human health (Fig. 1). Risks of viruses and control measures for the pandemic, such as disinfection and waste disposal, should be assessed in a timely manner for human health and ecosystems (Fig. 1).

3.1 Impacts of environmental factors on virus behaviors

The lifespan, diffusion, migration, and variation of infectious viruses in the environment are associated with various environmental factors. Studies on the impacts of environmental factors on virus behaviors are beneficial to the scientific prevention and control of pandemics. For example, viruses can be transferred by human respiratory droplets and aerosols, and the distance droplets and aerosols will transfer in the air is associated with the size, gravity, inertia, and evaporation of droplets [40]. Under indoor conditions, aerosols containing SARS-CoV-2 can be transferred further than 6 ft (1.8 m), whereas viral concentrations can be diluted more rapidly in outdoor environments by breezes and winds [41]. Furthermore, the attachment of viruses to dust and particulates can modify their aerodynamic characteristics and increase their dispersion. SARS-CoV-2 is se om 4 to 70 °C [11]. SARS-CoV-2 is also less stable on rough surfaces than on smooth surfaces, while it survives well at a relative humidity of less than 33% or of 100% [10]. However, the impacts of environmental factors on the behavior of the new variant of SARS-CoV-2 are unknown, although the variant is spreading at "an alarming rate" [42] in the United Kingdom and may be up to 70% more transmissible than SARS-CoV-2. Current studies on virus behaviors should be further strengthened to provide more scientifically relevant information for establishing effective control measures.

3.2 Minimization of secondary environmental risks

3.2.1 Scientific disinfection

During the pandemic, chemical agents have been widely used for the disinfection of municipal wastewater, village sewage discharge, streets, public areas, households, and communities, as this is the most convenient, widely used and low-cost method. However, sprinkled disinfectants end up in the ambient environment either directly or indirectly, thereby contaminating the environment, destroying ecosystems, and threatening the health of organisms including humans [7,43]. It has been pointed out that most disinfectants, such as sodium hypochlorite, are corrosive and irritate the mucous membranes of the respiratory and digestive tracts of mammals and birds [43]. In water, chlorinated disinfectants can result in disinfection byproducts, such as halomethanes, haloacetic acid, haloacetonitriles, inorganic halooxate, halonitromethane, cyanogen halides, and haloacetaldehyde, which are carcinogenic, teratogenic, and mutagenic [44]. Therefore, it is urgent to develop scientific and environmentally friendly means of disinfection and thus reduce the long-term risks for humans and ecosystems.

Proper disinfection methods should be developed and used. It has been demonstrated that SARS-CoV-2 is highly susceptible to far-ultraviolet radiation C (far-UVC) (222 nm) (Table 1) [45], which is safe for human skin and eyes. Thus, for indoor environments with poor ventilation, low-dose-rate far-UVC light could be used to safely reduce airborne coronaviral levels. Peracetic acid, 75% ethanol, and chlorinated disinfectants can inactivate SARS-CoV-2 effectively [46], while co-occurrence substances, such as organic matter, can decrease the sensitivity of viruses to disinfectants. Therefore, the mechanism of disinfection needs to be studied further in order to disinfect efficiently. Apart from the adoption of disinfection technology, shrinking the scope of human activity during a pandemic could efficiently reduce the usage of disinfection.

Table 1

Inactivation of SARS-CoV-2 by far-UVC light (222 nm) (0.1 mW·cm^{-2}) [45].

Inactivation time (s)	$TCID_{50}$ (mL)[a]	Log removal[b]
0	$(2.05 \pm 1.21) \times 10^4$	–
10	$(2.34 \pm 0.86) \times 10^3$	0.94
30	6.32 ± 0	2.51
60	6.32 ± 0	2.51
300	6.32 ± 0	2.51

[a] $TCID_{50}$: 50% tissue culture infectious dose (the data were means ± standard deviation); [b] Log removal: differences between $\log_{10}$ $TCID_{50}$ values recovered from plates after 222 nm far-UVC irradiation and those from nonirradiated samples.

3.2.2 Disposal of hazardous wastes

The COVID-19 pandemic has led to a massive increase in hazardous wastes, especially infectious medical wastes, which threaten human health and the functions of ecosystems. For example, medical wastes in Wuhan, China, increased from 40 t·d^{-1} to about 247 t·d^{-1} in less than 50 days after the onset of the COVID-19 pandemic [47]. Medical wastes in Kuala Lumpur, Manila, Bangkok, and Hanoi have increased to 154–280 t·d^{-1} more than the amount prior to COVID-19 [48]. The operation loads of disposal facilities for medical wastes in Hubei Province, China, were as high as 85%–96% in 2019 [49], and there was clearly a much greater need for medical wastes disposal during the subsequent pandemic. During the pandemic in China, massive amounts of hazardous wastes were incinerated by transporting them to nearby incinerators. In addition, more mobile emergency incineration facilities were built, and old incineration facilities for household wastes were rebuilt to facilitate the treatment of an increased amount of hazardous wastes [49]. However, incineration is not a sustainable method, as it has a high cost and may release harmful substances due to improper operation.

To reduce the socioeconomic and environmental impacts of waste disposal, sustainable methods that consider waste generation, collection, transport, treatment, recycling, and the disposal of the remaining waste residues are recommended [50]. Sustainable mobile treatment systems are also encouraged. Considering the instability of disposal facilities, the specificity of wastes produced during pandemics, and the lack of criteria for sampling and monitoring discharge, governments should rapidly establish standards for the exhaust from such emergency treatment facilities, and assess its environmental risks in order to minimize any negative impacts to the environment and human health.

Hazardous wastes do not only come from hospitals; they are also produced in households and public places. For example, masks can reduce airborne viral concentrations to protect uninfected individuals from SARS-CoV-2 aerosols and droplets [41]. Scientists and governments in many countries have encouraged people to wear masks in public places, and a large number of masks are being used and discarded over relatively short periods of time. Some of these masks are likely to have been contaminated by asymptomatic individuals and thus contain infectious viruses [41]. To avoid the further spread of infectious viruses during the pandemic, masks discarded in places other than hospitals should be treated separately from other form

and transporters should be disinfected in a timely manner, and the masks should be disposed of by qualified departments to decrease the risk of further dissemination of infectious viruses due to improper disposal measures. Meanwhile, workers dealing with the hazardous wastes should be equipped with protective masks, gloves, and clothing, as well as hand sanitizer, detergent, and other necessary protective equipment to ensure their safety.

3.3 Management of wastewater and minimization of further viral dissemination

3.3.1 Surveillance of viruses in wastewater

During a pandemic, the surveillance of viruses in wastewater must be enhanced in order to understand the disease burdens, changing trends, and resurgence likelihood of the pandemic [35]. This noninvasive method can be used to assess and manage the risks of viral dissemination, alert the authorities of a resurgence of the pandemic, guide officials to strengthen or withdraw lockdowns, and decrease the damage to health and the economy.

3.3.2 Treatment of viruses in wastewater

In general, conventional WWTP processes cannot remove viruses completely, and high influent viral loads during a pandemic may result in an insufficient reduction of viruses before discharge, for viruses such as rotavirus, sapovirus, astrovirus, and SARS-CoV-2 [51–53]. It has been shown that SARS-CoV-2 RNA was detected in a secondary-treated wastewater (2.4×10^3 copies·L^{-1}) in Japan [54], although another study showed that it was completely removed in the treated effluent of WWTPs with secondary biological processes [55]. These contrasting results indicate that there is a chance that virus occurrence in treated effluent and could carry the risk of triggering secondary transmissions. To ensure the inactivation of SARS-CoV-2, membrane filtration and disinfection by chlorinated disinfectants, UVC irradiation, and ozonation for treated effluents are necessary. For example, microfiltration and ultrafiltration are perfect barriers for SARS-CoV-2 when the pore size distributions on the membrane filters are less than the hydrated diameter of SARS-CoV-2 [56,57]; SARS-CoVs tend to be more susceptible to chlorinated disinfectants than enteroviruses [58]; and UVC irradiation at 254 and 222 nm can inactivate SARS-CoV-2 efficiently [9,45]. Co-occurrence matrices can affect the efficiency of virus removal, however [59]. More effective and low-cost methods should be rapidly developed to remove viruses effectively. In addition, discharge standards for WWTPs should include the monitoring of enveloped viruses based on appropriate indicators.

3.3.3 Management of wastewater from rural areas

During pandemics, wastewater in low-income areas—especially the feces and urine of humans and animals—must be given more attention, due to the general lack of sanitation infrastructure and WWTPs in these areas. According to the United Nations, about 9% of global residents defecate in the open, while another 8% use a facility that is shared with another household [60]. Even worse, the reuse of fecal and other organic wastes is encouraged in the rural areas of China, which greatly increases the risk of virus transmission.

To avoid further virus dissemination, the reuse of wastewater and excreta should be stopped immediately, and wastes should be disinfected by every household [59]. It is essential to strengthen the design, establishment, and management of sanitation infrastructures and WWTPs in low-income areas. Furthermore, governments should review and re-examine the regulations and standards for the safe disposal and reuse of fecal wastes, domestic sewage, and household wastes in rural areas.

3.4 Risk assessment

Infective virions in effluent and reused wastewater not only directly threaten human health, but also produce bioaerosols containing viruses [61]. It has been reported that the rates of emission of virions by aerosolization in the aeration basin of WWTPs are greater than those in toilets and lab-scale models, and the existence of solids does not mitigate the aerosolization of viruses [62]. Moreover, sprinkler irrigation using wastewater and fertilization using wastewater solids might also generate aerosols [59]. SARS-CoV-2 is infectious in aerosols for up to 16 h [31]. Accordingly, infectious aerosols threaten the health of relevant workers and nearby residents.

To avoid adverse effects on human health, the risks caused by viruses in wastewater and aerosols need to be quantified. The process of quantitative microbial risk assessment (QMRA) contains four steps (Fig. 3): hazard identification, exposure assessment, dose-response assessment, and risk characterization. QMRA has been used to assess the risks of some pathogens in water, aerosol, or food, such as legionella, mycobacteria tuberculosis complex, and influenza virus in aerosol; cryptosporidium, campylobacter, and rotavirus in drinking water; and adenovirus, enterovirus, hepatitis A virus, and norovirus in wastewater [61,63,64]. Recently, Zaneti et al. [65] investigated the potential health risks of SARS-CoV-2 in sewage for WWTP workers, and found that the estimated risks for the aggressive and extreme scenarios were likely to be above the derived tolerable infection risk for SARS-CoV-2. However, few assessments have been done on the risks of coronavirus using QMRA, so more studies are warranted.

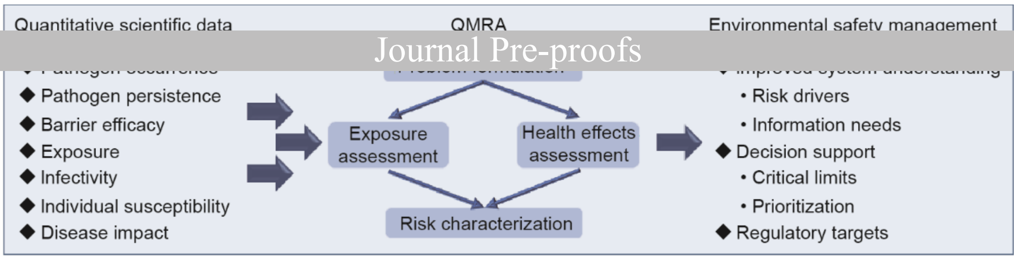

Fig. 3. QMRA: A tool for combining quantitative scientific data related to environmentally relevant disease pathways to support environmental safety management.

The secondary environmental risks produced during pandemic control should also be assessed in order to minimize the impacts to ecosystems and human health. For example, the main disinfection byproducts in regions where vast quantities of disinfectants are used and the harmful exhaust from treatment facilities for emergency medical wastes treatment should be assessed in a timely manner.

4. How can the probability of pandemic resurgence be reduced and normal activities be restored?

To avoid the resurgence of COVID-19 (after pandemic control), surveillance of SARS-CoV-2 in hotspots should be strengthened in comparison with that from before the COVID-19 pandemic. Residual secondary environmental risks should be assessed and controlled continuously to minimize the impacts of pandemics. Predicting the resurgence of COVID-19, considering the environmental and anthropogenic factors, is significant to enable timely responses to the next resurgence. To restore normal life and production among humanity, protection of the environment and wildlife should be maintained in order to minimize outbreaks of virus infections in the future and realize sustainable development (Fig. 1) [3,4].

4.1 Strengthened viral surveillance in the environment

During the post-pandemic period, the presence of the infectious virus that induced the past pandemic in the environment, such as in hotspots, should be surveyed more frequently and comprehensively than usual in order to prevent further dissemination of viruses and resurgence of the pandemic. For example, viruses in wet markets, including on or in chopping boards, knives, refrigerators, mops, wastewater, and meat and seafood products, as well as the workers related to booths selling frozen and chilled meats and seafood, should be monitored frequently. As mentioned above, it is recommended that virus surveillance be strengthened in other hotspots, such as cold-food supply chains, sanitation infrastructures, farms, slaughter-houses, WWTPs, and sewage pipes in communities. Governments should review and revise the regulations on viral surveillance and management frameworks in these hotspots.

4.2 Prediction of a pandemic resurgence considering environmental factors

To predict the resurgence of SARS-CoV-2 from near-term climate forecasts, more attention should be given to relationships among climatic variations, interventions, and the COVID-19 pandemic. Some simulations of the COVID-19 pandemic have been conducted, which found that summer weather would not limit COVID-19 growth substantially, strong outbreaks were likely to occur in more humid climates, and COVID-19 would become more dangerous again in the winter [66,67]. Nevertheless, longer term studies are warranted on the dynamics of SARS-CoV-2 that consider the influence of various environmental factors on a global scale. Scenario planning is useful to determine which prior actions are beneficial to building resilience and reducing disastrous effects for the next unexpected pandemic. It is important to predict unexpected situations—instead of assuming that the next crisis will be “just like this one”—in order to prevent unfortunate surprises [68].

4.3 Maintained protection of the environment to restore normal activities sustainably

As of 15 May 2020, the global economic losses have been estimated to be between $\$5.8 \times 10^{12}$ and $\$8.8 \times 10^{12}$ USD, which is equivalent to 6.4% to 9.7% of the global gross domestic product [69]. This figure does not begin to measure the suffering of and psychological impacts on the global public, which are catastrophic. Losses in education and social interactions that can never be replaced are mounting daily. These costs are so great that such a pandemic should be avoided at all cost in the future. However, in order to recover their economies, many countries have relaxed their protection of the environment. For example, India has cut the funding allocated to environmental protection and relaxed the requirements for industrial and infrastructural discharge [70], and the United States has canceled certain environmental guidelines and appears to plan to recover its economy through the use of nonrenewable resources [71]. It is unwise to relax environmental protection because doing so will increase the likelihood of future pandemic outbreaks. Following the pandemic, the premise of “One Health” and sustainability should be at the core of economic recovery. Decarbonization is specifically recommended as compatible with economic recovery, as it produces co-benefits for environmental protection, human health, and economic growth [72]. Furthermore, regulations for environmental protection should not be set aside, and collaboration across multiple departments is necessary [72].

Finally, the end of this COVID-19 pandemic is not the end of viral pandemics. Three coronaviral pandemics have already broken out, and another viral pandemic may break out in the near future [35]. Further studies on the integration of environmental factors into PHERSs are essential to respond to the next unexpected pandemic.

5. Conclusions

In recent decades, pandemic outbreaks of pathogenic viruses are becoming more frequent, challenging current PHERSs. Given the "One Health" concept and the connectivity of viruses in the biosphere, the environment plays an important role in regulating viral transmission and thereby influencing PHERSs. However, little attention has been given in PHERSs to the role of environmental factors as an intersection between environment and health. This study proposed that the significance of the environment needs to be considered before, during, and after responses to a pandemic by strengthening environmental protection, surveying viruses in the environment, improving early-warning systems, avoiding secondary environmental risks, minimizing the further dissemination of viruses, and predicting and preventing subsequent outbreaks. Overall, environmental factors should be integrated into future PHERSs by establishing systems and institutions of technical support, environmental response, and risk prevention, in order to improve national capabilities to respond to serious public health emergencies. Furthermore, relevant regulations and standards should be updated and improved to provide timely political support. The recommendations of this study are essential for improving national capabilities to respond to public health emergencies around the globe. The significant roles of environmental factors before, during, and after responses to public health emergencies must receive more attention in the near future.

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References

[1] WHO coronavirus disease (COVID-19) dashboard [Internet]. Geneva: World Health Organization; [cited 2020 Dec 21]. Available from: https://covid19.who.int/.
[2] Kissler SM, Tedijanto C, Goldstein E, Grad YH, Lipsitch M. Projecting the transmission dynamics of SARS-CoV-2 through the postpandemic period. Science 2020;368(6493):860–8.
[3] A coordinated global research roadmap: 2019 novel coronavirus [Internet]. Geneva: World Health Organization; 2020 March 12 [cited 2020 Dec 21]. Available from: https://www.who.int/publications/m/item/a-coordinated-global-research-roadmap.
[4] Transforming our world: the 2030 agenda for sustainable development [Internet]. New York: United Nations; 2015 Oct 21 [cited 2020 Dec 21]. Available from: https://sdgs.un.org/2030agenda.
[5] Dorsett M. Point of no return: COVID-19 and the U.S. healthcare system: an emergency physician's perspective. Sci Adv 2020; 6(26):eabc5354.
[6] Qu G, Li X, Hu L, Jiang G. An imperative need for research on the role of environmental factors in transmission of novel coronavirus (COVID-19). Environ Sci Technol 2020;54(7):3730–2.
[7] Zhang H, Tang W, Chen Y, Yin W. Disinfection threatens aquatic ecosystems. Science 2020;368(6487):146–7.
[8] Gibb R, Redding DW, Chin KQ, Donnelly CA, Blackburn TM, Newbold T, et al. Zoonotic host diversity increases in human-dominated ecosystems. Nature 2020;584(7821):398–402.
[9] Heilingloh CS, Aufderhorst UW, Schipper L, Dittmer U, Witzke O, Yang D, et al. Susceptibility of SARS-CoV-2 to UV irradiation. Am J Infect Control 2020;48(10):1273–5.
[10] Lin K, Marr LC. Humidity-dependent decay of viruses, but not bacteria, in aerosols and droplets follows disinfection kinetics. Environ Sci Technol 2020;54(2):1024–32.
[11] Chin AWH, Chu JTS, Perera MRA, Hui KPY, Yen HL, Chan MCW, et al. Stability of SARS-CoV-2 in different environmental conditions. Lancet Microbe 2020;1(1):e10.
[12] Mehmood K, Saifullah, Iqbal M, Abrar MM. Can exposure to $PM_{2.5}$ particles increase the incidence of coronavirus disease 2019 (COVID-19)? Sci Total Environ 2020;741:140441.
[13] Lister SA. An overview of the U.S. public health system in the context of emergency preparedness [Internet]. Washington, DC: Congressional Research Service Report for Congress. 2005 March 17 [cited 2020 Dec 21]. Available from: http://coherentbabble.com/CRS/CRS-RL31719[1].pdf
[14] WHO. International Health Regulations (2005) (Second edition) [Internet]. Geneva: World Health Organization; c2018 [cited 2020 Dec 21]. Available from: https://www.who.int/ihr/9789241596664/en/.tr
[15] Aitsi-Selmi A, Murray V. Protecting the health and well-being of populations from disasters: health and health care in the Sendai Framework for Disaster Risk Reduction 2015–2030. Prehosp Disaster Med 2016;31(1):74–8.
[16] Morawska L, Tang JW, Bahnfleth W, Bluyssen PM, Boerstra A, Buonanno G, et al. How can airborne transmission of COVID-19 indoors be minimised? Environ Int 2020;142:105832.
[17] Jacobsen KH. Will COVID-19 generate global preparedness? Lancet 2020;395(10229):1013–4.
[18] Buchanan M. Forewarned is forearmed. Nat Phys 2020;16(5):501.
[19] Dobson AP, Pimm SL, Hannah L, Kaufman L, Ahumada JA, Ando AW, et al. Ecology and economics for pandemic prevention. Science 2020;369(6502):379–381.
[20] World wildlife crime report 2020: trafficking in protected species [Internet]. Vienna: United Nations Office on Drugs and Crime; 2020 May [cited 2020 Dec 21]. Available from: https://www.unodc.org/unodc/en/data-and-analysis/wildlife.html.
[21] Ma J. Report on sustainable development strategy of China's wildlife farming industry. Technical Report. Beijing: Chinese Academy of Engineering. 2017. Chinese.
[22] Petrikova I, Cole J, Farlow A. COVID-19, wet markets, and planetary health. Lancet Planet Health 2020;4(6):e213–4.
[23] China's top legislature approves decision to ban illegal wildlife trade [Internet]. Beijing: China Global Television Network; 2020 Feb 24 [cited 2020 Dec 21]. Available from: https://news.cgtn.com/news/2020-02-24/China-s-top-legislature-approves-to-ban-illegal-wildlife-trade-OlrtorGko0/index.html.
[24] Wildlife markets and COVID-19 white paper [Internet]. Washington, DC: Humane Society International; 2020 Apr [cited 2020 Dec 21]. Available from: https://www.hsi.org/wp-content/uploads/2020/04/Wildlife-Markets-and-COVID-19-White-Paper.pdf.
[25] WHO Director-General's opening remarks at the Mission briefing on COVID-19 [Internet]. Geneva: World Health Organization; 2020 Apr 16 [cited 2020 Dec 21]. Available from: https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-mission-briefing-on-covid-19---16-april-2020.
[26] Zoonoses: beyond the human–animal–environment interface. Lancet 2020;396(10243):1.
[27] Wang H, Shao J, Luo X, Chuai Z, Xu S, Geng M, Gao Z. Wildlife consumption ban is insufficient. Science 2020;367(6485):1435.
[28] Hu B, Zeng LP, Yang XL, Ge XY, Zhang W, Li B, et al. Discovery of a rich gene pool of bat SARS-related coronaviruses provides new insights into the origin of SARS coronavirus. PLoS Pathog 2017;13(11):e1006698.
[29] Li H, Mendelsohn E, Zong C, Zhang W, Hagan E, Wang N, et al. Human–animal interactions and bat coronavirus spillover potential among rural residents in Southern China. Biosaf Health 2019;1(2):84–90.
[30] Watsa M; the Wildlife Disease Surveillance Focus Group. Rigorous wildlife disease surveillance. Science 2020;369(6500):145–7.

[31] Fears AC, Klimstra WB, Duprex P, Hartman A, Weaver SC, Plante KC, et al. Comparative dynamic aerosol efficiencies of three emergent coron

[32] Mohan SV, Hemalatha M, Kopperi H, Ranjith I, Kiran Kumar A. SARS-CoV-2 in environmental perspective: Occurrence, persistence, surveillance, inactivation and challenges. Chem Eng J 2021;405:126893.

[33] Liu C. Beijing supermarkets stop selling salmon after wholesalers test positive for coronavirus [Internet]. Beijing: Global Times; 2020 Jun 13 [cited 2020 Dec 21]. Available from: https://www.globaltimes.cn/content/1191462.shtml.

[34] Caruso BA, Freeman MC. Shared sanitation and the spread of COVID-19: risks and next steps. Lancet Planet Health 2020;4(5):e173.

[35] Nabi G, Siddique R, Khan S. Detecting viral outbreaks in future using enhanced environmental surveillance. Environ Res 2020;188:109731.

[36] CGTN. Has cold chain become the new hotbed for coronavirus? [Internet]. Beijing: China Global Television Network; 2020 Jun 21 [cited 2020 Dec 21]. Available from: https://news.cgtn.com/news/2020-06-21/Has-cold-chain-become-the-new-hotbed-for-coronavirus--RvbCN9vZ6w/index.html.

[37] Irradiation technology could be used in killing coronavirus on cold chain food packaging: China National Nuclear Corporation [Internet]. Beijing: Global Times; 2020 Dec 17 [cited 2020 Dec 21]. Available from: https://www.globaltimes.cn/content/1210303.shtml.

[38] Liu G, Qu J, Rose J, Medema G. Roadmap for managing SARS-CoV-2 and other viruses in the water environment for public health. Engineering 2021. In press.

[39] Peeling RW, Boeras D, Wilder-Smith A, Sall A, Nkengasong J. Need for sustainable biobanking networks for COVID-19 and other diseases of epidemic potential. Lancet Infect Dis 2020;20(10):e268–73.

[40] Tellier R, Li Y, Cowling BJ, Tang JW. Recognition of aerosol transmission of infectious agents: a commentary. BMC Infect Dis 2019;19(1):101.

[41] Prather KA, Wang CC, Schooley RT. Reducing transmission of SARS-CoV-2. Science 2020;368(6498):1422–4.

[42] Yan H. UK PM announces new stricter restrictions to combat coronavirus surge [Internet]. Beijing: XINHUANET; 2020 Dec 20 [cited 2020 Dec 21]. Available from: http://www.xinhuanet.com/english/2020-12/20/c_139603735.htm.

[43] Nabi G, Wang Y, Hao Y, Khan S, Wu Y, Li D. Massive use of disinfectants against COVID-19 poses potential risks to urban wildlife. Environ Res 2020;188:109916.

[44] Zhu H, Xue L, Liu J, Chen Y, Jin X, Yuan M. Types, hazards and pollution status of chlorinated disinfection by-products in surface water. Res Environ Sci 2020;33(7):1640–8. Chinese.

[45] Kitagawa H, Nomura T, Nazmul T, Omori K, Shigemoto N, Sakaguchi T, et al. Effectiveness of 222-nm ultraviolet light on disinfecting SARS-CoV-2 surface contamination. Am J Infect Control 2020;000:1–3.

[46] Yang P, Wang X. COVID-19: a new challenge for human beings. Cell Mol Immunol 2020;17(5):555–7.

[47] Li S, Hu Z. Medical waste treatment in Wuhan from emergency to stability [Internet]. Beijing: XINHUANET; 2020 Apr 1 [cited 2020 Dec 21]. Available from: www.xinhuanet.com/local/2020-04/01/c_1125796126.htm.

[48] Managing infectious medical waste during the COVID-19 pandemic [Internet]. Metro Manila: Asian Development Bank.; 2020 Apr [cited 2020 Dec 21]. Available from: https://www.adb.org/sites/default/files/publication/578771/managing-medical-waste-covid19.pdf.

[49] Sun N, Liu F, Zhang Y, Ding Z. Thoughts and suggestions on reinforcing the weakness of medical waste collection and disposal facilities in China. Environ Prot Sci 2020;46(3):120–6. Chinese.

[50] You S, Sonne C, Sik OKY. COVID-19's unsustainable waste management. Science 2020;368(6498):1438.

[51] Wurtzer S, Marechal V, Mouchel JM, Maday Y, Teyssou R, Richard E, et al. Evaluation of lockdown impact on SARS-CoV-2 dynamics through viral genome quantification in Paris wastewaters. 2020. MedRxiv 2020

[52] Qiu Y, Lee BE, Neumann N, Ashbolt N, Craik S, Maal-Bared R, et al. Assessment of human virus removal during municipal wastewater treatment in Edmonton, Canada. J Appl Microbiol 2015;119(6):1729–39.

[53] Carducci A, Battistini R, Rovini E, Verani M. Viral removal by wastewater treatment: Monitoring of indicators and pathogens. Food Environ Virol 2009;1(2):85–91.

[54] Haramoto E, Malla B, Thakali O, Kitajima M. First environmental surveillance for the presence of SARS-CoV-2 RNAin wastewater and river water in Japan. Sci Total Environ 2020;737:14045.

[55] Sherchan SP, Shahin S, Ward LM, Tandukar S, Aw TG, Schmitz B, et al. First detection of SARS-CoV-2 RNA in wastewater in North America: a study in Louisiana, USA. Sci Total Environ 2020;743:140621.

[56] Bodzek M, Konieczny K, Rajca M. Membranes in water and wastewater disinfection–review. Arch Environ Prot 2019;45:3–18.

[57] Tchobanoglous G, Burton FL, Stensel HD, editors. Wastewater engineering, treatment and reuse. 4th ed. New York: McGraw-Hill; 2004.

[58] Ye Y, Chang PH, Hartert J, Wigginton KR. Reactivity of enveloped virus genome, proteins, and lipids with free chlorine and UV 254. Environ Sci Technol 2018;52(14):7698–708.

[59] Bogler A, Packman A, Furman A, Gross A, Kushmaro A, Ronen A. Rethinking wastewater risks and monitoring in light of the COVID-19 pandemic. Nat Sustain 2020;3:981–90.

[60] Progress on household drinking water, sanitation and hygiene 2000–2017: special focus on inequalities. New York: United Nations Children's Fund (UNICEF), World Health Organization, 2019.

[61] Kitajima M, Ahmed W, Bibby K, Carducci A, Gerba CP, Hamilton KA, et al. SARS-CoV-2 in wastewater: state of the knowledge and research needs. Sci Total Environ 2020;739:139076.

[62] Lin K, Marr LC. Aerosolization of Ebola virus surrogates in wastewater systems. Environ Sci Technol 2017;51(5):2669–75.

[63] Qu L, Huang Z. Research progress of quantitative microbial risk assessment of drinking water. J Environ Health 2015;32(10):923–6. Chinese.

[64] Zhang B, Liu F, Bai X. Progress on health risk assessment of pathogenic microorganism aerosol. J Environ Hyg 2015;5:287–92. Chinese.

[65] Zaneti RN, Girardi V, Spilki FR, Mena K, Westphalen APC, da Costa Colares ER, et al. Quantitative microbial risk assessment of SARS-CoV-2 for workers in wastewater treatment plants. Sci Total Environ 2021;754:142163.

[66] Baker RE, Yang W, Vecchi GA, Metcalf CJE, Grenfell BT. Susceptible supply limits the role of climate in the early SARS-CoV-2 pandemic. Science 2020;369(6501):315–9.

[67] Scudellari M. Researchers are developing a host of scenarios to predict how the next few years might look. Nature 2020;584(7819):22–5.

[68] McNutt M. Lessons from the crucible of crisis. Science 2020;368(6492):683.

[69] COVID-19 economic impact could reach $8.8 trillion globally: ADB Report [Internet]. Beijing: XINHUANET; 2020 May 15 [cited 2020 Dec 21]. Available from: http://www.xinhuanet.com/english/2020-05/15/c_139058712.htm.

[70] Ellwanger JH, Lekgoathi MDS, Nemani K, Tarselli MA, Al Harraq A, Uzonyi A, et al. News from a postpandemic world. Science 2020;369(6499):26–9.

[71] Rosenbloom D, Markard J. A COVID-19 recovery for climate. Science 2020;368(6490):447.

[72] Fears R, Gillett W, Haines A, Norton M, ter Meulen V. Post-pandemic recovery: use of scientific advice to achieve social equity, planetary health, and economic benefits. Lancet Planet Health 2020;4(9):e383–4.