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Review

The effects of COVID-19 transmission on environmental sustainability and human health: Paving the way to ensure its sustainable management

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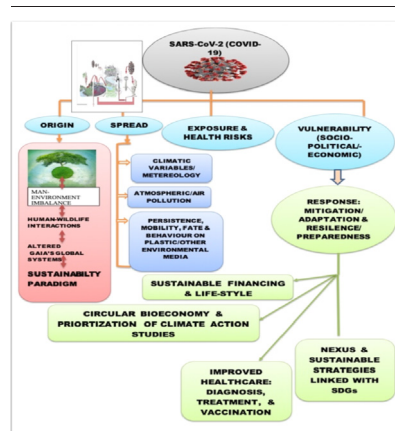
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HIGHLIGHTS

- Our knowledge is short on the transmission dynamics of COVID-19.
- The effects of COVID-19 are elucidated in relation to planetary public health and livelihood.
- The COVID-19 effects are envisioned in terms of environmental sustainability.
- The energy resilience, circular bioeconomy, 'nexus', and healthcare indicators are important.

GRAPHICAL ABSTRACT



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ABSTRACT

The transmission dynamics and health risks of coronavirus disease 2019 (COVID-19) pandemic are inextricably linked to interact with environment, climate, air pollution, and meteorological conditions. The spread of COVID-19 infection can thus perturb the 'planetary health' and livelihood by exerting impacts on the temporal and spatial variabilities of environmental pollution. Prioritization of COVID-19 by the health-care sector has been posing a serious threat to economic progress while undermining the efforts to meet the United Nations' Sustainable Development Goals (SDGs) for environmental sustainability. Here, we review the multifaceted effects of COVID-19 with respect to environmental quality, climatic variables, SDGs, energy resilience, and sustainability programs. It is well perceived that COVID-19 may have long-lasting and profound effects on socio-economic systems, food security, livelihoods, and the 'nexus' indicators. To seek for the solution of these problems, consensus can be drawn to establish and ensure a sound health-care system, a sustainable environment, and a circular bioeconomy. A holistic analysis of COVID-19s effects on multiple sectors should help develop nature-based solutions, cleaner technologies, and green economic recovery plans to help maintain environmental sustainability, ecosystem resilience, and planetary health.

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1. Introduction

Among many views on the Coronavirus disease 2019 (COVID-19), one may focus on zoonotic spillover associated with declining biodiversity and biotope deterioration in the Anthropocene (Lewis and Maslin, 2015; Rai, 2021a, 2021b). The complex transmission dynamics of COVID-19 adversely influenced the human health (Hinchliffe et al., 2021). Worldwide lockdowns after the outbreak of the first cases of COVID-19 resulted in positive as well as negative effects on environment and climate (Filho et al., 2021; Wyns and Daalen, 2021). Similarly, the COVID-19 disease ecology can also exert both positive and negative heterogeneous effects on biota, wildlife, and biological invasions (Mani, 2020; Guo and Lee, 2022). Incidentally, positive effects of lockdowns on environmental quality are not sustainable over an extended period due to short-term restriction of anthropogenic activities (Mikul'c'c et al., 2022).

The air quality, climatic, seasonal, and environmental factors played a vital role in epidemiology of COVID-19 infections, irrespective of regulatory measures such as lockdowns and vaccinations (Qu et al., 2020; Srivastava, 2021). The meteorological factors such as temperature and humidity were tightly linked with spread of COVID-19 infections and human health risks (Ma et al., 2020). Therefore, the effects of transmission dynamics of COVID-19 are recognized as ‘air pollution-to-human’ rather than ‘human-to-human’ transmission. As such, the dominant role of gaseous and particulate matter (PM) is acknowledged as active media to spread infections and associated mortality (Coccia, 2020a).

The environmental sustainability is inextricably linked with the spread of COVID-19 infections (Coccia, 2020b). The increased prices of renewable energy sources such as natural gas during COVID-19 resulted in revitalization of coal and nuclear power production with negative effects on climate (Mikul'c'c et al., 2022). The increase in the electricity demand during COVID-19 by about 43%, disruption in global supply chains, and energy intensive vaccination programmes adversely influenced the climate action efforts (Kleme's et al., 2020; Jiang et al., 2021). The spread of COVID-19 has also derailed progress on meeting the United Nation's 17 Sustainable Development Goals (SDGs) by disrupting global efforts to alleviate imminent threats to natural resources and has adversely influenced agriculture, forestry and agro-forestry, livelihoods, food security, nutrition, education, and global peace (Nundy et al., 2021). Although global efforts are being made to address COVID-19, sustainability and “nexus” indicators have yet to be fully incorporated into policy development aimed at its mitigation (Barouki et al., 2021; Kleme's et al., 2020; Rai et al., 2022). For example,

a report from the Humanities in the European Research Area (HERA, 2020) emphasizes the need for more research on how to make ecosystems, the climate, and human health and welfare more resilient in the midst of COVID-19 due to a growing gap between our knowledge of COVID-19's effects and appropriate mitigation strategies.

In recent years, the effects and management of COVID-19 have been based largely on empirical studies (Kleme's et al., 2020; Rai et al., 2021c; Rai et al., 2022). For example, although initial trends indicated a reduction in environmental pollution after the outbreak of COVID-19, the available data are insufficient to assess the long-term ecological implications (McNeely, 2021). Assessments of the initial effects of COVID-19 and its evolving variants (e.g., delta, lambda, and omicron) on temporal environmental recovery during world-wide lockdowns have also overlooked the long-term perspective (Guo and Lee, 2022). Several studies suggest that the frequent lockdowns were more common and compulsive to countries with poor or moderate healthcare infrastructure (Coccia, 2021). However, the lockdowns further exacerbated the sustainable economic growth without noticeable effect on the reduction in COVID-19 mortality.

In the past studies, information on the effects of COVID-19 focused on individual sectors such as health, pollution in the form of plastic and solid waste (Barouki et al., 2021; Rai et al., 2022), environmental quality (Lovejoy, 2021), climate variables and meteorological parameters (Fattorini and Regoli, 2020), and energy footprints (Kleme's et al., 2020). The effects of COVID-19 on several consequential issues (e.g., environmental quality, human health, agriculture, livelihood, and renewable energy) have been addressed in an integrated manner in a few studies such as Giurca et al. (2022) and Mikul'c'c et al. (2022). Previous studies did not explore the inter-relationship between the SDGs and nexus indicators (e.g., water-energy-food [W-E-F]) in sufficient depth to adequately describe the effects of the pandemic (Magazzino et al., 2021; Nhamo and Ndlela, 2021). The present review was therefore designed to elucidate the effects of COVID-19 in an integrated manner by covering key sectors, such as environment, human health, agriculture, and socio-economy.

In this review, the information was collected from the database of Scopus, Science Direct, and PubMed generated mostly between January 2020 and March 2022. The quest of scientific literature was confined to the keywords such as ‘COVID-19 and Environment or climate’, ‘COVID-19 and air pollution’, ‘COVID-19 and human health’, ‘COVID-19 and Environmental Sustainability’, ‘COVID-19 and Sustainable Management’, ‘COVID-19 and energy’, and ‘COVID-19 and SDGs’. This systematic review has thus been synthesized to assess the effects of COVID-19 on environment and climate as they can

play a crucial role in transmission dynamics and associated health risks. Further, the effects of COVID-19 on human health and well-being in terms of livelihood are described to elucidate its societal damages. In addition to planetary health, the effects of pandemic on SDGs, nexus, energy resilience, and circular bioeconomy are critically evaluated to expand the horizon of sustainable COVID-19 management (Fig. 1). The significance of COVID-19 risks, vulnerability, adaptation, resilience, preparedness, recovery, and mitigation is addressed through lens of SDGs. Consequently, we carried out a critical review of diverse issues associated with COVID-19, such as growing environmental footprints, climatic effects, growing risks to human health and well-being, and transformation of the energy sector.

Visualization of multiple sectors can provide an explicit or holistic overview of the global challenge of synthesizing sustainable, pragmatic, and ecosystem-based solutions. We conclude that studies on the multifaceted influences of COVID-19 should involve parallel assessments of both sustainability and nexus indicators. The present review is expected to help improve planetary health by delineating the links between COVID-19s effects and nexus indicators. This evaluation is intended to be used to

develop pragmatic research frameworks for viable and environmentally sustainable strategies against COVID-19.

2. COVID-19 effects on environmental quality

The effects and aftermath of COVID-19 have attracted unprecedented attention, particularly with respect to environmental quality. Lockdowns to control the spread of severe acquired respiratory virus coronavirus 2 (SARS-CoV-2), the virus that causes COVID-19, are responsible for environmental degradation through the generation of increasing amounts of biomedical waste (up 300%–400%), solid and plastic wastes (up 200%), atmospheric ozone (up 10%–60%), and indoor and outdoor air pollutants (Chowdhury et al., 2021; Rai et al., 2021a, 2021b, 2021c). In general, amelioration of declining environmental quality during COVID-19 due to reduced industrial emissions was short-lived, while adverse effects due to human efforts to overcome the pandemic are likely to persist over longer periods of time (Srivastava, 2021). Although the immediate positive effects of COVID-19 on environmental quality were initially received as a “window of opportunity,” their long-term consequences need in-depth investigation with respect to ecosystem resilience, climate action, and ecological sustainability (Lehmann et al., 2021) (Table 1).

2.1. Air quality

The spread of COVID-19 was tightly linked with the changes in air quality indices such as the levels of ambient PM₁₀/PM_{2.5}, gaseous pollutants (eg., nitrogen dioxide (NO₂) ozone (O₃) and carbon monoxide (CO)), and local weather conditions (Srivastava, 2021). During COVID-19, NO₂ and carbon emissions decreased by 25%–30% in major cities of China (Facciola et al., 2021). Likewise, 71% decreases in PM levels were reported in several major metropolitan cities in India (e.g., Delhi, Mumbai, Chennai, Kolkata, and Hyderabad) (CPCB, 2020). In northern Italy, a significant decrease in hazardous air pollutants was seen in levels of benzene, CO NO₂, PM₁₀, and PM_{2.5} (Collivignarelli et al., 2020). The health risks from COVID-19 are tightly linked with the air quality, as the spread of SARS-CoV-2 as aerosols can be affected by meteorological factors such as temperature, humidity, wind speed, visibility, and rainfall (Chen et al., 2020). Cities with low air quality levels around the world generally experienced significantly higher rates of COVID-19 infections and mortalities (Fattorini and Regoli, 2020; Ali and Islam, 2020). The concentrations of small-sized fractions of PM and other atmospheric contaminants such as O₃, volatile organic compounds, CO, and NO₂ are highly correlated with the exacerbation of health risks in COVID-19 patients (Glencross et al., 2020; Sharma et al., 2021).

The residence time of SARS-CoV-2 in air or atmospheric components (e.g., dust) is another crucial factor determining the epidemiology of COVID-19 (Qu et al., 2020). In the city of Wuhan, China, COVID-19 deaths were reportedly associated with variations in temperature and humidity (Ma et al., 2020). Urban air pollution and corresponding climate variables exacerbated COVID-19 mortality and morbidity, creating challenges for both public health authorities and epidemiologists (Fattorini and Regoli, 2020). In this respect, Hinterlands were noted with higher COVID-19 infections than coastal regions. As such, geographical determinants can also influence the factors governing the meteorological or air pollutant dispersion to exert controls on the spread dynamics of COVID-19 (Coccia, 2020a).

2.2. Aquatic life and toxicology

Marine ecosystems such as coral reefs were reported to be at least partially revitalized during COVID-19 lockdowns (Soto et al., 2021). Venice Lagoon in Italy was reportedly rejuvenated due to improvements in the health of several aquatic organisms and ecosystems, as well as reduced tourism and transportation activities (Braga et al., 2020). The water quality of freshwater ecosystems such as the Ganges River in India was also significantly ameliorated (Mani, 2020). Therefore, COVID-19 allowed for “nature-based solutions” to restore aquatic ecosystems (Lovejoy, 2021). On the other, perturbations in aquatic ecosystems were apparently due to the

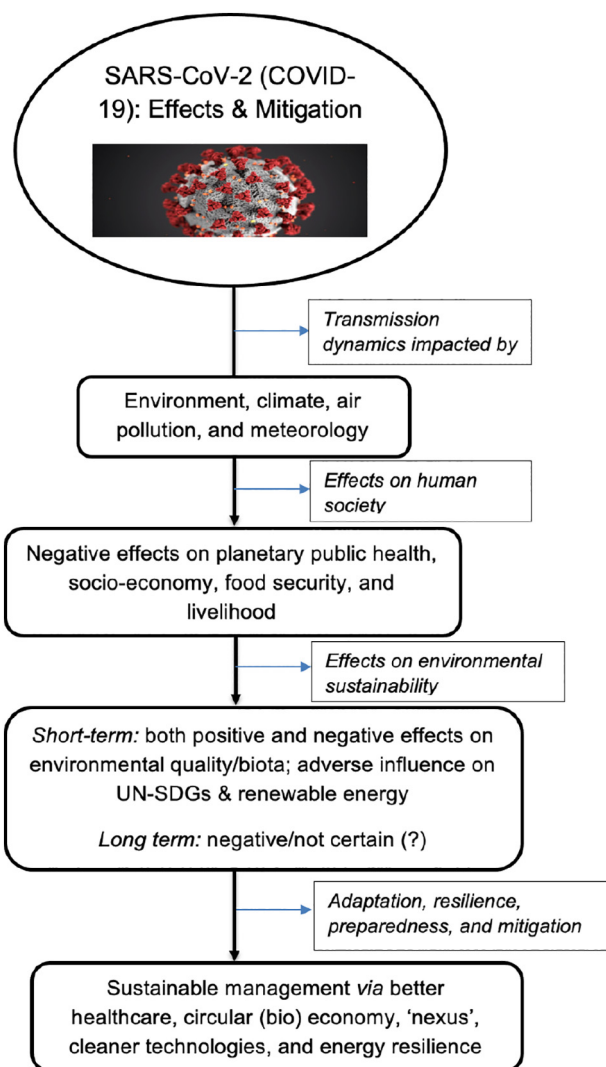


Fig. 1. Transmission dynamics of COVID-19 and multiple effects on environment, climate, human health, food security, energy, and sustainable livelihoods. The effects of COVID-19 were mixed (both +ve and -ve) in terms of environmental quality (air, water, soil, and noise pollution), biota, and revitalization of aquatic ecosystems. The positive effects were usually short-term warranting long-term COVID-19 mitigation plan mediated through improved healthcare, circular bioeconomy, nexus, and energy resilient approaches.

Table 1
Short/long-term positive and negative influence of COVID-19 on environmental quality, biodiversity, and wild life at national and global scales.

Serial number	Country (city)	Environmental (biotic & abiotic) matrix	Short term + ve/- ve effects Parameter influenced during lockdown associated with spread of COVID-19	Long term effects on environmental sustainability	References
1.	Global perspective	Solid/plastic waste in multiple matrices	Negative (-ve) due to excessive disposal of biomedical waste	Negative (-ve)	Kleme's et al. (2020); Rai et al. (2022)
2.	Global biodiversity	Aquatic & terrestrial	Positive (+ve) due to less anthropogenic interference & -ve due to lack of conservation practices	Both +ve & -ve	Guo and Lee (2022)
3.	India (Hyderabad, Kolkata, Mumbai)	Air	10%–54% decline in ambient PM ₁₀ levels; decline in ambient PM levels up to 71% + ve effects on air quality	Not certain	Kumar (2020); CPCB (2020)
4.	China and other countries	Air	30% decline in ambient NO ₂ levels; 25% reduction in carbon emissions; + ve effects on climate action	Not certain/temporary	Facciola et al. (2021)
5.	Italy (Milan)	Air	Decreased concentrations of SO ₂ (25.4%, CO (57.6), No (41.3%), benzene, and PM _{2.5} (47.1%–47.4%); while increase in ozone (O ₃) levels, +ve effects on gaseous pollutants but -ve effects on ground level O ₃ deleterious to food crops	Not certain but future sustainability implications	Collivignarelli et al. (2020)
6.	Global analysis	Air, water, and soil	Increased fecal pollution in wastewater treatment plants but decline in soil and noise pollution + ve effects on air/noise pollution but -ve effects on water purification	Not certain	SanJuan-Reyes et al. (2021)
7.	Biotic invasions	Aquatic & terrestrial	+ ve due to less human mediated introductions & -ve due to inadequate management practices	Both +ve & -ve	Guo and Lee (2022)
8.	Italy and UK	Noise	Up to 50% decline in ambient noise levels inextricably linked with cardiovascular diseases + ve effects on noise pollution amelioration and human health	Not certain/temporary	Antza and Stabouli (2020)
9.	United States	Air	Decline in NO ₂ (49%) and CO (37%) + ve effects on air quality	Not certain	Chen et al. (2020)
10.	Brazil (Rio de Janeiro)	Air	Decline in PM ₁₀ levels by 15%–33.3%, NO ₂ (28.5%) and CO (40.3%) + ve effects on air quality	Not certain	Dantas et al. (2020)
11.	Global perspective	Human/wildlife health	-ve	-ve/not certain	McNeely, 2021
12.	Italy (Venice)	Marine ecosystems	Revitalization of Venice lagoon with enriched aquatic biodiversity + ve effects on marine biodiversity	Not certain	Braga et al. (2020)
13.	India (sacred landscapes of the Ganges basins)	Freshwater ecosystems	Amelioration in water quality/physical-chemical parameters + ve effects on water quality	Temporary	Mani (2020)
14.	Global scale	Global climate	CO ₂ emissions decreased by 17% + ve effects on climate change mitigation	Temporary	Le Le Quéré et al. (2020); Liu et al. (2020)
15.	Global scale	Global climate	Decline in GHGs by 4%–7% + ve effects on climate action	Temporary but lessons for future sustainability	Rugani and Caro (2020); Cooper (2020)

prolonged persistence of the coronavirus in inadequately managed sewage treatment plants and aerosolized wastewater pathways (Bogler et al., 2020). Wastewater and municipal waste treatment plants can act as central nodes of COVID-19 infection (Bogler et al., 2020).

Widespread application of traditional disinfectants such as strong oxidants (e.g., sodium hypochlorite, peracetic acid, and hydrogen peroxide) and ultraviolet light can attenuate SARS-CoV-2 levels in wastewater (Carraturo et al., 2020). However, large-scale application of these oxidants to control COVID-19 can have undesirable side effects. For example, excessive use of sodium hypochlorite may produce high levels of disinfectant by-products, which can be transformed into more hazardous halogenated organic compounds (García-Ávila et al., 2020; SanJuan-Reyes et al., 2021). A shortage of safe disinfection technology can accelerate viral spread with enhanced chemical pollution (Bogler et al., 2020).

3. COVID-19 effects on climate

The COVID-19 pandemic influenced climate and climatic variables, both of which are tightly linked to the epidemiology of the disease (Filho et al., 2021; Lovejoy, 2021). Imminent global threats of COVID-19 were exacerbated through changes in climatic variables (Watts et al., 2021). The synergy produced by the concurrency of COVID-19 and climatic variables is directly associated with human health risks (Nundy et al., 2021). Recent environmental disasters, including a massive flood in China, have also been attributed to the combined effects of climate and

COVID-19 (Guo et al., 2020). However, climate action research is often overlooked due to prioritization of COVID-19-specific health-care facilities and biomedical science (Atwoli et al., 2021). In fact, the predicted health risks of an increase of >1.5 °C in the global average temperature may exert more catastrophic effects than those induced by COVID-19 (Atwoli et al., 2021). Similarly, Jiao et al. (2020) also predicted that the irreversible environmental challenges and health risks linked with climate can be even more severe than the impact of COVID-19 (Jiao et al., 2020). Moreover, the interactive effects of climate and COVID-19 have jeopardized the resilience of rural ethnic communities by perturbing indigenous socio-ecological systems and food security (Zavaleta-Cortijo et al., 2020). However, the larger picture of climate-related disasters and human health hazards has not received adequate attention (Jiao et al., 2020). Potential risks and vulnerability from climatic fluctuations require more scrutiny during COVID-19 in the form of increased social awareness of relevant ecological indicators (Jiao et al., 2020; Rai and Singh, 2020).

To help reduce the risks of COVID-19, more efforts should be put to address the effects of climate on the pandemic. For example, the UN General Assembly biodiversity summit in Kunming, China, in September 2021, and the 2021 UN Conference of the Parties (COP26) in Glasgow, UK, attempted to streamline climate action and mitigation mechanisms (Atwoli et al., 2021). The COVID-19 crisis has since emerged as a wake-up call for global institutions to integrate their efforts to cope with negative effects on climate.

The effects of COVID-19 lockdowns on multiple environmental matrices or transport/industrial sector and their influence on global climate can be

too early to predict. After the onset of the pandemic in 2020, daily global CO₂ emissions declined by 17%, although the decline was not sustainable in the long term (Le Le Quéré et al., 2020; Liu et al., 2020). A brief decrease in global greenhouse gas (GHG) emissions (4% to 7%) was observed due to the COVID-19 crisis–led “anthropause” in economic and public transport restrictions (Le Le Quéré et al., 2020). The temporary decline in GHGs emissions during COVID-19 lockdowns can be attributed to dramatic reductions in human activities (e.g., the lowering of petroleum consumption in view of restricted transport, tourism, and industrial or manufacturing activities) (Rugani and Caro, 2020; Cooper, 2020). The positive influence on climate trends due to situation-specific declines in GHGs during COVID-19 cannot be validated in terms of their long-term effects on environmental sustainability (McNeely, 2021). On the contrary, the COVID-19 crisis adversely influenced climate action due to larger carbon footprints and electricity consumption during prolonged home stays (Filho et al., 2021).

The initial positive impacts on environmental amelioration during COVID-19 were suspected to be short-lived, with negligible contributions to long-term climate action (Le Le Quéré et al., 2020; Forster et al., 2020; Pianta et al., 2021). In addition, declining trends in GHG emissions were spatially variable across continents and countries (Pianta et al., 2021). For example, a study of three distinct landscapes (Burkina Faso, Colombia, and France) showed that this short-term decrease in CO₂ emissions can be attributed to a decrease in crop exports (Andrieu et al., 2021). According to a study on reduced CO₂ emissions during the COVID-19 pandemic in the energy sector of the United States, declines in GHGs were statistically significant only in April and May of 2020 (Luke et al., 2021).

Climate directly influences meteorological and environmental factors, and air pollutants exacerbate respiratory health complications of COVID-19 patients (Ma et al., 2021). Appropriate epidemiological studies are therefore required to identify vulnerable populations based on climate and environmental data and air quality factors (Ma et al., 2021). These data can help mitigate the health hazards caused by COVID-19 infections. Despite the low predictability of COVID-19 impacts on climate, the potential of such aspects needs to be investigated over the long term (e.g., taking into account the dynamics of climatic variables, mitigation policies, and interactions with socio-ecological/socio-economic systems) (Van Dam and Webbink, 2020; Filho et al., 2021).

With respect to financial incentives, ecologists are concerned about the diversion of resources from climatology to COVID-19 and health-care systems (Shan et al., 2021; Wyns and Daalen, 2021; Pianta et al., 2021). Although monetary or financial incentives to fulfill climate targets have been strengthened, enforcement of personal carbon allowances has not been evenly distributed, giving more leeway to nations with powerful economies (Nerini et al., 2021). Nationally determined contributions (NDCs) to achieving Paris Agreement targets (restricting global average temperature rise to well below 2 °C) were not able to equitably incorporate COVID-19 into climate mitigation policies (Wyns and Daalen, 2021). Government-commissioned reports indicate that COVID-19 had mixed influences on climate goals, with positive impacts on 15 NDCs but negative effects on 14 NDCs (Wyns and Daalen, 2021). However, the sustainability prospects for climate action were adversely influenced by short-term declines in GHGs during lockdowns and a lack of low-environment-impact COVID-19 recovery measures (Wyns and Daalen, 2021). Nevertheless, the allocation of financial incentives to support environmentally friendly COVID-19 recovery was relatively low (e.g., “about one fifth of fiscal spending” in 2020), undermining the climate goals of developing nations (O’callaghan and Murdock, 2020). Environmentally friendly recovery measures for COVID-19 and climate targets received attention in only 9 of 48 proposed NDCs, attenuating the sustainability framework of climate action policies (Wyns and Daalen, 2021). The “green” recovery of the COVID-19 pandemic, ecosystem restoration, and climate action needs to be uniformly addressed in tandem with equitable financial incentives to help achieve planetary human health and well-being, as well as environmental sustainability.

4. COVID-19 effects on society: planetary health and livelihoods

4.1. Human health

The COVID-19 pandemic significantly perturbed planetary public health in terms of mortality and morbidity. As of 12 March 2022, the World Health Organization (WHO) estimated that >6 million people died due to COVID-19 while about 452 million had been infected, faced with acute respiratory and cardiovascular problems (WHO, 2022). In addition to imposing direct hazardous effects on human health, COVID-19 weakened the holistic health-care system as it attempted to cope with overwhelming numbers of COVID-19 patients (Huet et al., 2020; Mesnier et al., 2020; Paris, 2021).

Among human organs, the prime targets of the delta and lambda variants of the coronavirus are lung tissues, with a wide variety of impacts reported (Dickson, 2021). Unlike the omicron variant, the earlier variants disrupted alveolar immune responses and lung microbiota (Dickson, 2021). Along with general human health indicators, socio-economic, environmental, clinical, and specific genetic factors of infected hosts also contribute to the severity of COVID-19. For example, according to meta-analyses of genome maps of 49,562 patients with COVID-19 in 19 countries, 13 genome loci appeared to be intimately associated with COVID-19 infection (Dickson, 2021). Autoimmune and inflammatory disease responses after COVID-19 infection are therefore suspected to be linked to the genetic make-up of the human population. Specific genome loci affect the severity of COVID-19 infection and host-specific responses; this could help identify clinical and therapeutic options and health-risk mitigation policies (COVID-19 Host Genetics Initiative, 2021). At the molecular level, the health risks from COVID-19 have been demonstrated to emanate from disruption of cytokine/immune signaling, endothelial cells, neutrophil infiltration, and thrombosis of the lung (Lee et al., 2021). Multiple health effects of certain COVID-19 variants can act together to induce cellular apoptosis in the lungs, which can lead to severe respiratory problems.

The severity of human health risks from COVID-19 can be exacerbated when linked with aging, climate variables, air quality, cardiovascular diseases, and respiratory ailments (Barouki et al., 2021). Atmospheric pollution (both gaseous and PM) can exacerbate respiratory health risks associated with COVID-19. Biochemically, damage to respiratory organs is amplified through elevated reactive oxygen species that induce oxidative damage and generate abnormal DNA adducts (Rai, 2016). Oxidative stress in conjunction with abnormal genetic regulation can cause carcinogenicity and mutagenicity, mitochondrial dysfunction, fibrosis, and stimulation of pro-inflammatory responses. Smaller aerosols (PM_{2.5} and PM_{0.1}) in conjunction with pathogenic microbes can penetrate deep inside the lungs by multiplying or proliferating within alveoli (Comunian et al., 2020).

In patients with COVID-19, the risks of PM_{2.5} from household cooking in low- and middle-economy countries can further increase the risks to human health (Rao, 2021; Ravindra et al., 2021). High levels of environmental contaminants in air can increase COVID-19 mortality and morbidity (Comunian et al., 2020; Facciola et al., 2021). In addition to direct respiratory and cardiovascular effects, COVID-19 can indirectly compound mental and neurological disorders. A meta-analysis of 227 million people in 21 countries found a relationship between COVID-19 and mental and neurological disorders (Liu et al., 2021). COVID-19 can also exacerbate pre-existing psychological neural disorders in non-infected individuals and induce fear or stress symptoms in infected patients (Liu et al., 2021). Psychological or mental stress during COVID-19 can reduce immunity and induce cardiac abnormalities, creating a need to prioritize related health-care studies (Liu et al., 2021). Children tend to be prone to physical and mental health risks due to their social, cultural, economic, and physical environments (Suarez-Lopez et al., 2021). Changes in educational environment, tourism restrictions, and limited opportunities for outdoor activities can result in psychological distress, particularly in children with pre-existing health risks (Suarez-Lopez et al., 2021).

4.2. Effect on livelihood

COVID-19 lockdowns imposed negative effects on livelihoods by disrupting agricultural activities and economies (Dobson et al., 2020; Rowan and Galanakis, 2020). Indigenous rural populations were reportedly under severe socio-economic distress during COVID-19 due to the loss of livelihoods and limited access to indigenous food resources (Anderson et al., 2016; Zavaleta-Cortijo et al., 2020; Ruiz-Salmón et al., 2021). The adverse effects on agriculture created problems in nutritional security and maternal and pediatric health-care in low- and middle-income nations (Osendarp et al., 2021). For example, 11.9 million children are believed to have suffered from malnutrition during the pandemic, with childhood mortality estimated at 168,000 worldwide (Osendarp et al., 2021). In the context of livelihood, 'integrated multi-trophic aquaculture' (IMTA) is identified as sustainable food process with positive effects on climate. Incidentally, the extreme environmental variance during 2020 caused an adverse influence on bacteria and algae in IMTA to promote the dominance of toxic cyanobacteria (O'Neill et al., 2022). The released phycotoxins resulted in the mortality of fishes, especially *Perca fluviatilis* (European perch), *Oncorhynchus mykiss* (rainbow trout) (O'Neill et al., 2022).

Indigenous food systems are also adversely influenced by the COVID-19 crisis, worsening global poverty (UNO Info, 2020; Zavaleta-Cortijo et al., 2020). Due to the direct link between agro-forestry and the livelihoods of marginalized peoples, more emphasis on environmentally sustainable, inclusive, resilient, and climate-smart agriculture is needed to ensure food security (Ruiz-Salmón et al., 2021). Newly emerging biotechnological tools such as nano-biofortification of food crops have been identified to address malnutrition and strengthen immunity. However, modified food crops with fortified immunity booster nutrients can be costly and they rarely reach rural populations (El-Ramady et al., 2021). The adverse effects of COVID-19 on health, livelihoods, poverty, and hunger need to be elucidated in appropriate frameworks (WEO, 2020; World Food Programme, 2020; Filho et al., 2021). Strengthening of the agriculture and indigenous food sectors and livelihoods is required to ensure food security, nutrition, and human well-being.

5. Energy resilience, SDGs, and nexus prospects in COVID-19

5.1. Energy resilience

The COVID-19 pandemic has had multiple impacts on the energy sector and energy footprints (Jiang et al., 2021). Due to shutdowns in the industrial and transportation sectors, global energy consumption declined in its earlier phase (Klemeš et al., 2020). However, extended stays at home resulted in a temporal shift in energy demand, creating higher loads on electrical grids (Nundy et al., 2021). Prolonged lockdowns increased reliance on energy-intensive devices needed for education or job-related work. These new patterns suggest a need for energy-efficient buildings to maintain progress toward environmental sustainability (Nundy et al., 2021).

The production of renewable energy can result in sustainable environment which can minimize the spread of COVID-19 infections (Coccia, 2020b). Increased generation of solid and plastic wastes during COVID-19 also adversely affected the renewable energy industry (Jiang et al., 2021). Disposable facemasks were reportedly undermining the anaerobic digestion of municipal solid wastes, decreasing methane production by up to 18% (de Albuquerque et al., 2021). COVID-19 also impeded the transportation of renewable energy to households in developing nations that rely on unsustainable biomass (e.g., wood-fired cooking) (Ravindra et al., 2021; Rao, 2021).

COVID-19 disrupted subsidies to facilitate the use of renewable energy (Tsao et al., 2021). The UN's SDGs can only be achieved by integrating multiple programs, such as those designed to boost renewable energy supplies in rural or suburban regions, balance irrigation in favor of clean water, and impose carbon taxes (Barbier and Burgess, 2020). Deploying renewable

energy systems, conserving water resources, and developing biorefineries can all contribute to a circular economy and sustainable rural development.

Strengthening resilient elements of the energy sector is also necessary to address hardships experienced in health, socio-economic, and climate-action research (Jiang et al., 2021). Resilient energy systems offer flexibility to stakeholders seeking to establish low-carbon and carbon-neutral economies in the wake of COVID-19 (Heffron et al., 2021). Although the COVID-19 disease is considered a "major landscape shock," it has opened a path forward for a variety of opportunities to introduce low-impact alternatives to conventional power generation (Kanda and Kivimaa, 2020; Pianta et al., 2021). Envisioning energy sustainability during COVID-19 can help chart a path toward environmental sustainability (Elavarasan et al., 2021).

5.2. Sustainable development goals

The UN's SDGs were formulated in 2015 to help achieve environmental sustainability and planetary public health and improve human well-being by the year 2030. However, COVID-19 retarded timely attainment of 17 of the SDGs and adversely influenced ecosystem resilience, livelihoods, and human health (Fig. 2). The effects of COVID-19 on global society, economies, and ecosystems have made timely attainment of SDGs difficult (Barbier and Burgess, 2020). During COVID-19, health-safety goals linked with SDG 3 were prioritized whereas the other 16 SDGs received less attention. The editors of *Lancet Public Health* (Editors, 2020) expressed concern with diminished efforts to alleviate poverty; 6% of the global population are still expected to face extreme poverty by 2030. COVID-19 has put 71 million people into acute poverty, representing a major hurdle to achieving SDG 1 (poverty reduction). Economic recessions incurred by COVID-19 aggravate inequalities in health care, food security, and access to clean water around the world, severely undermining SDGs 2, 3, 6, and 10. Moreover, SDG 4 (inclusive and equitable access to education) was significantly hampered by COVID-19, particularly in countries with poor telecommunication infrastructure (Barbier and Burgess, 2020). COVID-19 lockdowns also undermined SDG 5 (gender equality) due to excessive workload stress on females, which resulted in a 30% increase in reports of global domestic violence (Berchin and de Andrade, 2020). The sustainability paradigm in governance, bioeconomy, and livelihoods needs to be redefined to mitigate the multiple effects of COVID-19. In addition, SDGs 16 (promote peace and safety from violence) and 17 (strengthen international partnerships) were disrupted during COVID-19 (Berchin and de Andrade, 2020). The adverse influences on SDGs 16 and 17 have been attributed to global disagreements over how to take responsibility for COVID-19's origin and spread, socio-economic inequality, inequity in health care, and a failure to export essential medicines.

The influence of the pandemic on energy resilience and bioeconomies is also tightly linked with SDGs (Woźniak and Tyczevska, 2021). Inadequate progress toward progress on SDG 1 has forced rural people to use biomass-based fuels for household cooking, which in turn makes SDG 7 (clean energy) and SDG 13 (climate action) harder to achieve. During COVID-19, the replacement of clean energy with biomass-based fuels by impoverished rural people worsened the air pollution (Mikul'čić et al., 2022). Pollutants from burning biomass pose threats to human health while interfering with SDGs 1–5, 7–8, 11, 13, and 15. According to a critical meta-analysis, the replacement of biomass with solar arrays and wind turbines can accelerate progress on SDG 7 (Elavarasan et al., 2021). Prioritization of renewable bioresource projects is therefore necessary during the COVID-19 era to bolster energy resilience and circular bioeconomies (Mikul'čić et al., 2022).

The effects of COVID-19 need to be assessed from social, political, economic, environmental, and ecological perspectives (Patterson et al., 2021). The pandemic has redefined the strategies, concepts, and attainment of environmental sustainability from a long-term perspective (Guo and Lee, 2022). Massive vaccination drives should also be validated in terms of life-cycle and sustainability indicators (Mikul'čić et al., 2022). However, a recent study of life-cycle assessments for COVID-19 vaccination programs

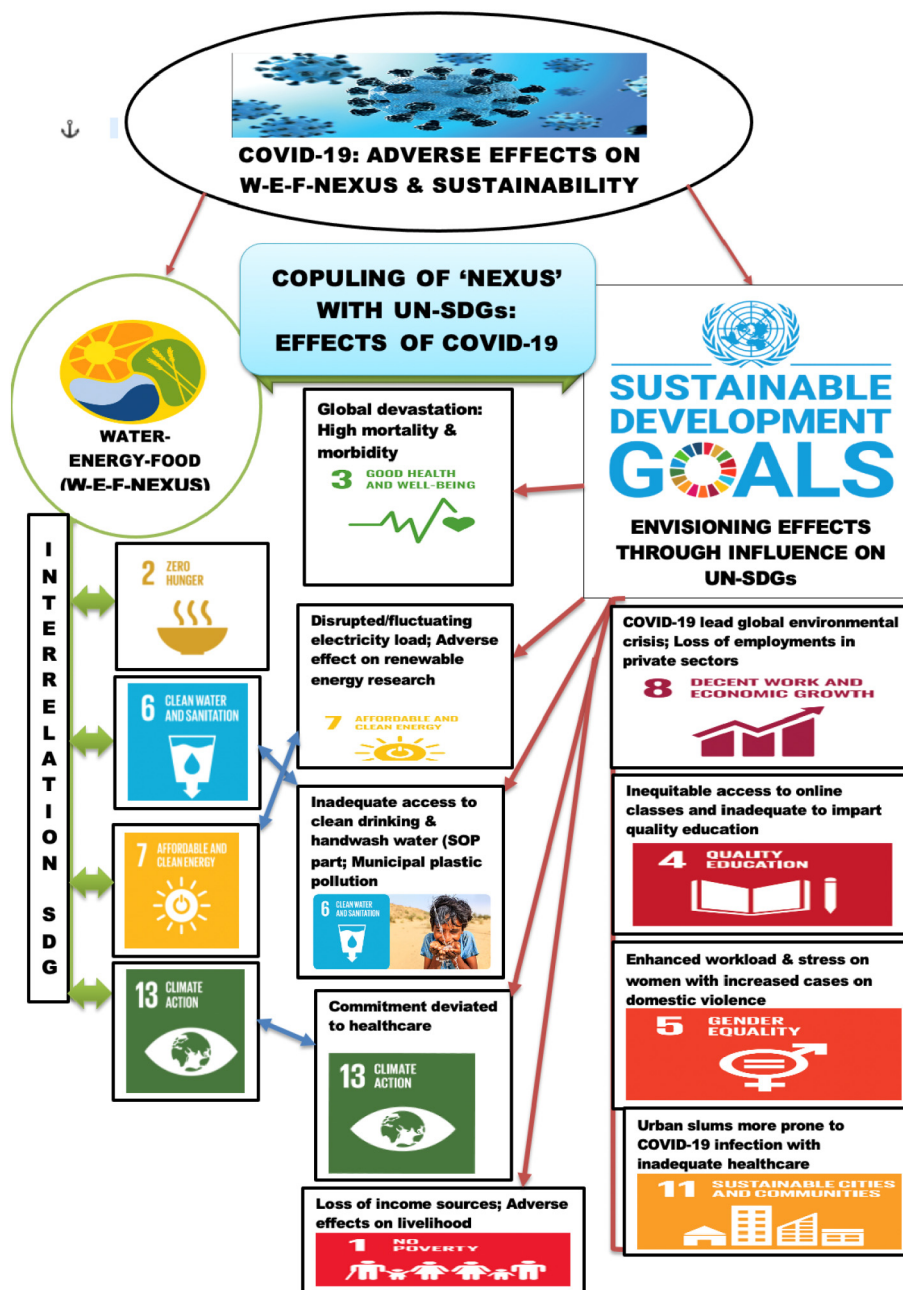


Fig. 2. Effects of COVID-19 on “SDGs-W-E-F Nexus” can influence ecosystem resilience, climate action, renewable energy, planetary health and sustainability. The pragmatic evaluation of the effects of COVID-19 on SDGs and nexus indicators can facilitate the formulation of sustainable management or mitigation approaches.

based on the 4Es (energy, environmental, economic, and [social] equity) indicated that this approach is unsustainable and serves as an impediment to meeting SDGs (Jiang et al., 2021). The 4E life-cycle assessment of COVID-19 vaccination drives also indicated that such energy-intensive pathways would adversely affect SDG 7. Global institutional efforts should be integrated to help achieve sustainability in COVID-19 vaccination drives (Jiang et al., 2021; Mikulčić et al., 2022).

As with energy policy and technology, climate action is inextricably linked with SDGs (Klemeš et al., 2020). However, the current regulatory agenda on climate action (i.e., SDG 13 and the Paris Agreement on climate change) is being compromised by the effects of COVID-19 (Wyns and Daalen, 2021). Adverse influences of COVID-19 on SDG 13 also affects SDG 1, according to 56 sustainability indicators (Sörgel et al., 2021). It has been suggested that the schedule for meeting 17 of the SDGs should be amended with a “pandemic reset” that extends the time limit to 2050 (Naidoo and Fisher, 2020; Sörgel et al., 2021). However, several

researchers argue that COVID-19 has facilitated the identification of obstacles to the SDG pathway (Ottersen and Engebretsen, 2020). They contend that, instead of revisiting the SDG time-frame, earmarking and addressing the challenges to their timely attainment would be more useful. In brief, the COVID-19 pandemic exacerbated health-care challenges and threats to environmental sustainability (Rai et al., 2022). Nevertheless, it helped identify gaps in global policies on environmental sustainability and encouraged the adoption of sustainable mitigation mechanisms in multiple sectors, including energy, rural livelihoods, human well-being, and climate action research.

5.3. The “nexus” perspective

It has now been widely established that the effects of COVID-19 are interrelated. From the nexus perspective, the coronavirus outbreak may be an outcome of anthropogenic disruption in the “land use–food–wildlife” nexus

of the horseshoe bat (Santini, 2021). However, attempts to mitigate individual environmental aspects of the effects of COVID-19 may not be sustainable if other problems are left unaddressed. Studies have revealed that the incorporation of linear and monocentric approaches neither mitigate the effects of COVID-19 nor enhance long-term ecosystem resilience or sustainability (Nhamo and Ndlela, 2021). For ecosystem-based sustainable solutions to COVID-19 effects, a nexus perspective can be extremely useful. To address the interrelated effects of COVID-19, pragmatic identification of trade-offs among environmental issues and the nexus approach is therefore necessary for integrated COVID-19 management, climate action, livelihood protection, and human well-being (Liu et al., 2018). Without an inclusive nexus approach, we cannot identify the integrated COVID-19-related actions we need to take that can also mitigate threats to socio-ecological and socio-economic systems (Nhamo and Ndlela, 2021). For example, in New York, a deep-learning machine was used to establish a nexus among health (in terms of COVID-19-induced mortality), air pollution (e.g., PM₁₀, PM_{2.5}, and NO₂), and socio-economic status (Magazzino et al., 2021). In the nexus perspective, a W-E-F nexus was devised by the World Economic Forum in 2008 to address environmental challenges in a holistic way (Fig. 2). However, the W-E-F nexus was forced to deviate from its original target due to the prolonged global effects of COVID-19 (Berchin and de Andrade, 2020).

An explicit interaction in W-E-F nexus perspectives among SDGs has been identified for energy (SDG 7) and climate action (SDG 13) (Elavarasan et al., 2021). Food security, particularly when associated with poor people, was widely undermined during lockdowns and quarantines, despite several government measures (Galanakis, 2020). Progress toward the first two SDGs (1 and 2), which are inextricably linked with the W-E-F nexus, has been undermined by increases in poverty and acute hunger due to COVID-19. The nexus of human health, climate change, water and food security, energy, and social justice/livelihood should also be addressed in an integrated way to mitigate the impact of the pandemic (Fig. 2). Incorporating nexus studies into sustainability science could help address multiple environmental issues, facilitate circular bioeconomies, and help reach 17 SDGs.

6. Mitigation of COVID-19 effects

6.1. Sustainable management

The recent emergence of new viruses is believed to be the result of 'natural zoonotic spillover' from wildlife species threatened by deforestation and unregulated wildlife trade (Dobson et al., 2020). Since the emergence of COVID-19 is either ascribed to zoonotic spillover or accidents in laboratories, there is an urgent need to prioritize environmental sustainability and to strengthen biosafety measures (Coccia, 2022). Effective modelling of ecosystem dynamics in global forests is required to better understand the connection to COVID-19 (Felipe-Lucia, 2021). Pre-emptive maintenance of natural sustainability would cost a small fraction of what is now being spent on managing the health hazards emanating from disruptions of ecosystems, as exemplified by the emergence of the COVID-19 pandemic (Dobson et al., 2020). Encouraging natural sustainability by minimizing deforestation and regulating the wildlife trade can help control viruses related to epidemics and pandemics, including COVID-19 (Dobson et al., 2020). However, existing strategies to mitigate COVID-19s effects are not typically based on sustainable and ecosystem-oriented solutions.

Strengthening socio-ecological and socio-economic resilience will be essential to achieving environmental and agricultural sustainability (Cawthorn et al., 2021). In this sense, studying the containment of disease-transmission mechanisms and how to foster immunity, and tracing the role of environmental factors in spreading coronaviruses can help create strategies for the mitigation of the COVID-19 pandemic (Cawthorn et al., 2021).

For sustainable management of COVID-19, collaborative efforts to achieve sustainable development with proper controls on human health risks are necessary (Bouman et al., 2021). The role of stakeholders and organizations in embracing sustainable lifestyles and in acknowledging a

societal responsibility for natural resource conservation is of paramount importance (Bouman et al., 2021). Several regulatory measures such as European Green Deal (EGD), Bioeconomy Strategy (BES), or Circular Economy Action Plan (CEAP) are suggested as options for sustainable management of COVID-19. In this aspect, EGD received wider public acceptance as revealed by media analysis and Delphi study, i.e., structured communications with international experts (Giurca et al., 2022). The wider acceptance of EGD was ascribed to its immediate visible effects in socio-economic, energy, food security, and waste management sectors (Giurca et al., 2022).

The implementation of sustainable environmental, healthcare, and institutional strategies can help mitigate the effects of COVID-19 (Mikul'číc et al., 2022). Sustainable lifestyles can encourage the development of resilient energy systems through judicious use of electrical or electronic devices in both low- and high-income households (Jiang et al., 2021). In addition to the adoption of sustainable lifestyles, encouraging the biorefineries and circular economies can be vital for improved planetary health during COVID-19 (Rai, 2021a, 2021b). As payable charges or incentives such as "home energy managing systems" as practiced in New York are still in their infancy, they are not ready for implementation in the developing world (Chen et al., 2021). Human well-being supported by sound healthcare systems should be maintained in tandem while prioritizing sustainable development and climate change mitigation. Coordinated responses to global environmental degradation should explicitly help identify synergies and trade-offs for inclusive or holistic mitigation of COVID-19s effects (Bouman et al., 2021). In the wake of COVID-19, regulatory institutions such as the World Health Organization should prioritize policy development to simultaneously safeguard human health and promote environmental sustainability (Monti et al., 2021). In this context, regional networks such as Pan-European Commission on Health and Sustainable Development with a crucial Pandemic Treaty can help the 53 member states in the WHO European Region address the effects of COVID-19 (Monti et al., 2021).

Because COVID-19 is widely perceived as imbalance in the "triad" (human, wildlife, and the environment), a holistic triad equilibrium with sustainable management approaches should be prioritized to prevent the re-emergence of COVID-19 (Monti et al., 2021). Although anthropogenic perturbations adversely influence ecosystem resilience and sustainability, humans can play a vital role in achieving the SDGs (e.g., through the control of "Gaia's balance"). The Gaia definition for delineating a social, economic, and environmental framework can augment the sustainable development pathway with judicious use of technological and natural resources (Berchin and de Andrade, 2020). Several indices such as 'Index r (resilience)' and 'index p (preparedness/prevention)' can be vital in mitigating the effects of COVID-19 (Coccia, 2022).

Biomedical measures such as surveillance and pharmaceuticals, along with clinically validated traditional and indigenous non-pharmaceutical treatments, can also be formulated to minimize the health risks of COVID-19. However, an explicit reappraisal of financial, political, socio-ecological, socio-economic, and global institutional incentives in planetary public health is urgently needed to improve human well-being during the pandemic (Hinchliffe et al., 2021). Concerned stakeholders should popularize the benefits of vaccination in decreasing the vulnerability of human populations toward SARS-CoV-2 infection and restrict the associated placebos or false rumors of their side-effects. Strengthening or popularizing clinically approved biomedical treatment methods should also be favored over non-pragmatic claims of alternative therapeutic products sold as cures for COVID-19.

Despite the intense pathogenicity of SARS-CoV-2, knowledge of its persistence in multiple environmental matrices (soil, plastic polymers, metallic surfaces, textiles, glass, air, and water/wastewater effluents and sewage sludge or biosolids) can help establish successful strategies for pandemic mitigation (Carraturo et al., 2020). The techno-economic advances and life-cycle assessments of "photoreforming" (solar power-driven innovation to reclaim municipal solid waste through the production of renewable hydrogen) can also contribute to sustainability and a carbon-neutral future (Uekert et al., 2021). COVID-19 sparked a global race to publish articles related to the pandemic in an attempt to attract more citations, irrespective of

quality (e.g., approximately 50 articles on COVID-19 have been retracted) and/or to make claims of applicability to human health care. Since the advent of pandemic-facilitated work-from-home arrangements, viable lifestyles now requires faster internet services, cleaner environmental designs, greater incorporation of plastic and bio-medical waste management, and explicit urban planning (Chowdhury et al., 2021; Rai et al., 2021b). The science-policy-human well-being interface needs to be bridged by integrated research programs to help achieve sustainable development.

6.2. Innovations in biomedical sciences

Global diagnostics for the management of coronaviruses can be facilitated by archiving specimens and pathogens (“biobanking”) and embracing economically feasible point-of-care tests for low- and middle-class populations (Peeling et al., 2020). Sustainable biobanking networks can also help diagnose and control COVID-19, as suggested by success stories from previous pandemics (e.g., the ZikaPLAN biobank during outbreak of the Zika virus). Biobanking can also provide equitable, ethical, and transparent solutions to the present pandemic as it tends to incorporate the underlying principles of the Nagoya Protocol (“Access to Genetic Resources”) and the Convention on Biological Diversity (“Fair and Equitable Sharing of Benefits”) (Peeling et al., 2020). Recent advances in molecular biology, such as clustered regularly interspaced short palindromic repeats (CRISPR), can provide a basis for coronavirus diagnoses (Broughton et al., 2020). In COVID-19 testing, the CRISPR-based Cas12a guide RNA/Csm9 tandem assay has proven to be a rapid, portable, and cost-effective replacement for polymer chain reaction amplification. In biomedical fields, sampling studies that elucidate the effects of coronaviruses on lung functioning can help determine the alterations in microbiota and the consequent heterogeneous effects on alveoli, which can mitigate health hazards (Dickson, 2021). Recent advances in nanoscience can also accelerate progress in the biomedical sector. The effectiveness of face masks, which work on colloid/interface principle, can further be enhanced by the introduction of outer coatings of silver nanoparticles and/or graphene/derivatives (e.g., polygrene) as additives (Liao et al., 2021). Incorporation of digital technologies in biomedical science (e.g., data management for early surveillance, testing, contact tracing, and quarantine, as implemented in South Korea) and health-care policy development can also play a vital role in the containment of COVID-19 (Whitelaw et al., 2020).

6.3. Circular (bio)-economy

The pandemic affected the circular economy, which is inextricably linked to the nexus indicator paradigm (Woźniak and Tyczewska, 2021). Both bioeconomies and nexus indicators emphasize the use of renewable biological resources for materials, food, and energy (Rai, 2021a, 2021b). To cope with COVID-19s effects, a bioeconomy approach is among the most promising options (O'Neill et al., 2022). The quest of cleaner technologies based on the principles of circular bioeconomy is needed to tackle the environmental sustainability challenges during COVID-19 (Mikul'ci'c et al., 2022). Existing gaps in research and development of diagnoses, vaccines, clinical trials, and mitigation measures for COVID-19 can be bridged through sustainable global financing to augment circular bioeconomy approach (Lurie et al., 2021; Mikul'ci'c et al., 2022). The UN (2020) also emphasizes regional mobilization in the financial sector and the allocation or more resources to strengthen circular bioeconomies during COVID-19. Providing the agri-food sector with “green new deal” approaches (e.g., paludiculture, comprising wet peatland innovation) can address the geopolitical and socio-economic constraints encountered during the pandemic (Rowan and Galanakis, 2020; O'Neill et al., 2022). Paradigm shifts in bioeconomy through sustainable agricultural practices can also help boost food security for impoverished populations, who have faced serious challenges over the past two years (Priyadarshini and Abhilash, 2021). The extension of “planetary healthy diets” for impoverished populations can address food insecurity and strengthen immunity against COVID-19 (Priyadarshini and Abhilash, 2021). Agro-ecosystem-management

prospects can therefore enhance the nutritional quality of food crops, strengthen immunity, and nurture circular bioeconomies.

7. Conclusions

Zoonotic spillovers can be the root cause of COVID-19 origin while its transmission dynamics was tightly regulated by the interaction between climatic and environmental variables. The perturbations in air quality and changes in meteorological factors exacerbated the COVID-19 infections and associated health risks. Sustainable management options for atmospheric pollution are therefore needed in view of their inextricable links with COVID-19 morbidity and mortality. The spread of COVID-19 had a substantial impact on environmental quality, climates, planetary or human health and well-being (livelihood), sustainability, and bioeconomies. Short-term improvements in selected measurements of environmental quality during COVID-19 can be seen as a pseudo-silver lining that must be validated through future study. Such efforts should include public assessments of the long-term effects on SDGs, energy resilience, climate action, and environmental sustainability. The multiple effects of COVID-19 can be explicitly envisioned through the lens of SDGs and by their relationship with sustainability and nexus indicators. Pragmatic evaluation of COVID-19s effects can improve our understanding of the vulnerability, preparedness, and potential mitigation strategies for sustainable management. The incorporation of resilient energy systems, circular bioeconomy, cleaner technologies, and nexus approaches can facilitate the sustainable management of COVID-19. Further advancements in scientific knowledge, health-care and biomedical disciplines, and sustainability science are required to bolster resilience in ecosystems and energy supplies, mitigate the negative effects of COVID-19, build sustainable societies, and prevent future pathogenic outbreaks.

CRedit authorship contribution statement

Prabhat Kumar Rai: Investigation, Methodology, Data curation, Formal analysis, Writing – review & editing. **C. Sonne:** Conceptualization, Formal analysis, Writing – review & editing. **H. Song:** Conceptualization, Formal analysis, Writing – review & editing. **Ki-Hyun Kim:** Conceptualization, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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