Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Review article

Environmental health research and the COVID-19 pandemic: A turning point towards sustainability

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ABSTRACT

Based on a review of COVID-19 research from an environmental health perspective, this study theorizes the interdependence of the society, environment and health, and presents an integrated framework for environmental health problems arising due to COVID-19. Five guiding principles are proposed for conducting environmental health research, including employing a transdisciplinary approach, embracing complexity and uncertainty, addressing vulnerability, boosting resilience and promoting sustainable development. This study propagates that the pandemic could be an opportunity for sustainable transformation, wherein visionary leadership that facilitates sustainability policies based on environmental health science is required. This study can serve as a consolidated guide for professionals and stakeholders who conduct environmental health research in this challenging field.

1. Introduction and study design

Studies of the transmission dynamics of coronavirus disease 2019 (COVID-19) have found that several environmental factors can affect COVID-19 transmission. These factors include meteorological factors, outdoor and indoor air quality, relative humidity, water and wastewater, fomites, solid waste, and soil (Núñez-Delgado, 2020; Race et al., 2020; Rahimi et al., 2020). For example, there are strong concerns regarding the factors that influence airborne transmission of COVID-19, including air quality index, particulate matter, NO_2, and temperature (Domingo et al., 2020). In fact, the spread of coronavirus could be considered air-pollutant-to-human transmission rather than direct human-to-human transmission, as the concentration of air pollutants combined with low wind speed promotes the process (Coccia, 2021b). Furthermore, interdisciplinary studies on environmental and sustainable science are also highly relevant. Coccia (2020b) proposed the dynamic exposure risk factors for epidemics such as COVID-19, which are based on socioeconomic and demographic, climatological, and environmental factors. The air quality implications arising in unsustainable environments can affect the spread of COVID-19 (Coccia, 2020a). The pandemic was initially considered a healthcare crisis; however, due to the recognition of the interdependent nature and complexity of various environmental health issues, the crisis can be more accurately considered a global environmental health issue.

Furthermore, the pandemic is dramatically reshaping the world and it presents a huge challenge to ensuring long-term sustainability in the post-COVID-19 era (Chakraborty and Maity, 2020). For instance, there is a growing concern that the pandemic may undermine the United Nations Sustainable Development Goals (SDGs) to end poverty by 2030, as global poverty may increase for the first time since 1990 (Sumner et al., 2020). However, this crisis could also be considered an opportunity for transformation, and the SDG framework could function as a useful guide to identify integrated solutions while minimizing the negative trade-offs (Tonne, 2021).

The current situation has thus made it clear that our health and wellbeing are delicate, interconnected, and dependent on the health of other people, animals and the planet. There is an urgent need for research that addresses the fundamental interdependence of society, the environment, and every being's health. Collective action needs to be taken to deal with the societal, health and environmental challenges we face. These challenges brought about by COVID-19 call for a holistic approach to dissect the complex and multifaceted interactions within the various domains.

With the goal of creating a sustainable strategy to manage future global crises, this study addresses the following research questions: What are the environmental health problems caused by the COVID-19

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pandemic? What is environmental health, and what are the key guiding principles of environmental health research? How can sustainable development be achieved in the post-COVID-19 era? This paper provides an overview of the research related to the COVID-19 pandemic, and highlights the interdependence of environmental health issues. It also attempts to provide guiding principles for environmental health research to address current challenges, promote environmental health studies, and achieve long-term sustainability.

This study systematically identifies and reviews relevant literature, based on the selection method proposed by Kumar et al. (2019). The review is based on a comprehensive search of peer-reviewed, scientific English publications in the Google Scholar search engine and PubMed databases, using various combinations of the following keywords according to Boolean search string strategy: COVID-19, coronavirus, environmental health, sustainable development, and sustainability. These searches retrieved articles that were published before February 28, 2021. The process of collection and identification of literature for the study ensured that relevant high-impact literature was systematically collated. To identify research priorities and formulate the best applicable recommendations, the existing knowledge was synthesized by critical analysis of the literature and a foundation laid for presenting the complex environmental health problems arising due to COVID-19, and in addition, guiding principles for environmental health research were proposed.

The rest of this paper is organized as follows. First, a theoretical framework for environmental health research is presented, where environmental health is positioned as a complex interdependence of the environment and health within a socioeconomic structure. This concept is then reviewed in two parts. The first part deals with environmental health problems arising due to COVID-19. The second part proposes the guiding principles of environmental health research in response to COVID-19 and beyond. To conclude, the findings are discussed, and the policy implications are presented.

2. A framework of environmental health research

A variety of methods have been proposed to define environmental health (Ahmad et al., 2019; Frumkin, 2016). To clarify the meaning of the concept, the definitions of environment and health are first discussed. “Environment” can be conceptualized in various ways and from different perspectives, which could vary from the most inclusive to the most restrictive (Pruss-Ustun et al., 2006). Thus, the boundaries of “environment” should be defined based on the focus of the question (Sauvé et al., 2016). Here, the physical environment, which defines the environment as external conditions and surroundings that affect the quality of life of humans, animals and plants, is emphasized. The physical environment includes both built and natural environments. The built environment includes buildings, spaces, and transportation systems that are created or modified by people, while the latter refers to an environment that is not the result of human intervention (Northridge et al., 2003).

The physical, psychological and social elements of an individual’s health and well-being influence each other, and the society also has an impact on the perception of the health and well-being of an individual. Thus, we address the concept of “health” at both the individual and the population levels. The current definition of environmental diseases and the environmental exposure assessment criteria need to be broadened and improved (Sly et al., 2016). According to the WHO, 24% of global deaths are linked to the environment; there were roughly 13.7 million deaths in 2016, indicating that almost one-quarter of the global disease burden is linked to unhealthy environmental conditions (World Health Organization, 2020a). Additionally, it has been identified that the determinant factors of health include the social and economic situation, physical environment, and the individual’s characteristics and behavior (Marmot and Wilkinson, 2005). Based on the inequality in health conditions, these factors interact within the different layers and can be used to guide environmental health research and trace the paths from socioeconomic structure.

Epidemiological studies have successfully identified the potential risk factors for diseases. However, the identification of individual-based risk factors is inadequate. Attention needs to be paid to social factors, such as socioeconomic status and social support, as these affect disease outcomes through multiple mechanisms (Link and Phelan, 1995). Furthermore, the developed society disrupts ecology, increases people’s vulnerability to diseases, and facilitates disease transmission, and these consequences affect all aspects of society and human health.

To achieve sustainable development, the interconnected systems co-evolving across spatial and temporal scales that influence the balance between health and socio-ecological systems have to be taken into consideration (Whitmee et al., 2015). Thus, the scope of environmental health research is not limited to merely public health, as the contribution and collaboration of the social sciences offer great potential for improving public and environmental health (Cordner et al., 2019).

The definition of environmental health proposed in this study includes the dynamic and complex interdependence of the environment and health within the socioeconomic structure. This would improve the understanding of the interconnections between social determinants, human well-being and the physical environment, including the potential for preventing adverse effects and would contribute toward ensuring a long-term sustainable environment. The conceptual framework (Fig. 1) illustrates the domains of environmental health research and the connection between them. A socio-ecological systems approach is required to facilitate holistic studies (Virapongse et al., 2016). This would also address the implications of environmental health interventions in the reduction of social inequalities, environmental degradation, and health disparities (Schulz and Northridge, 2004).

3. Results

3.1. Complex environmental health problems arising from COVID-19

- Society

Wide-ranging sociological issues have arisen due to the global impact

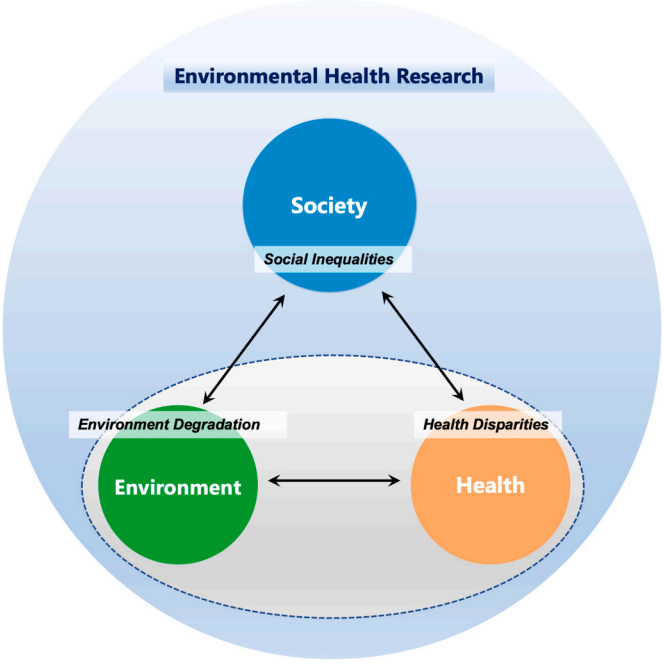

Fig. 1. A framework of environmental health research: integrating the issues of society, environment and health.

of the COVID-19 outbreak. Measures such as social distancing, household quarantine, and travel restrictions have been effective in limiting the transmission (Chinazzi et al., 2020). However, due to these restrictions, the workforce across all economic sectors has been reduced, which has sparked the fear of an economic crisis and worldwide recession (Nicola et al., 2020). The unemployment rate increased dramatically and participation in the labor force declined by seven percentage points globally, triggering a massive global unemployment crisis (Coibion et al., 2020). As international travel has been restricted, the effect of the pandemic on the tourism industry may be seen for a long period even after lockdowns are eased (Gössling et al., 2020).

At the same time, the burdened healthcare systems around the world have been struggling to respond to the global health emergency. The pandemic is testing all national health systems. A recent WHO global pulse survey found that 90% of the world's countries have reported disruptions to essential health services since the COVID-19 outbreak (World Health Organization, 2020b). Furthermore, the well-being of the healthcare workforce is the cornerstone of the healthcare system. The overwhelming burden and increased workload that the pandemic has put on these providers could lead to caregiver burnout (Moazzami et al., 2020). For instance, COVID-19 has had an impact on maternal and neonatal health services globally, and the number of institutional childbirths has fallen by half, while the rates of stillbirths and neonatal mortality have risen dramatically during the lockdown (Ashish et al., 2020). This crisis demonstrates the need for basic infection prevention and control measures, and the importance of ensuring that these minimum requirements are effectively implemented (Hopman et al., 2020).

This crisis has also challenged the food supply chain. Disruptions induced by COVID-19 have had an impact on all four factors associated with food security: availability, access, utilization, and stability (Laborde et al., 2020). To resolve the profound disruptions, a transformative food supply chain is needed (Mollenkopf et al., 2020). For example, consumers reacted to the disruptions by hoarding products in anticipation of food shortages, and there has been a dramatic shift in shopping behavior from physical store purchases to online shopping. Many people have been struggling to afford food because of job losses and the shifting demand for food pantries. Additionally, farmworkers are not available to harvest crops because of the sudden shift in demand and related regulations. This is in addition to the short-term disruptions in eating habits that have led to food loss and wastage due to the lockdowns (Aldaco et al., 2020).

Many countries have implemented national school closures as a response to the pandemic. However, this situation might turn an initial health issue into educational inequality that will have long-lasting consequences, especially for children from low-income families. For instance, school closures exacerbate food insecurity as schools are a place for learning and healthy eating for many students from a background of poverty. Furthermore, non-school factors are the primary sources of inequalities in educational outcomes (Van Lancker and Parolin, 2020). Even though this situation has accelerated the opportunities for remote teaching (Lyons et al., 2020), the accessibility of students to online learning platforms is determined by their family situation and social factors. Moreover, a large-scale, rapid shift to teleworking (work from home or home office) happened during the lockdown period, and this has created a need for the development of public policies for the emerging work arrangement (Organisation for Economic Co-operation and Development, 2020). In addition, not only did the coronavirus spread rapidly, but it also led to misinformation, including misleading rumors and conspiracy, which resulted in widespread panic and unhelpful measures (Depoux et al., 2020). Information overload, false information, and frequent social media exposure are associated with a high prevalence of mental health problems (Gao et al., 2020).

- Environment

The global response to the pandemic led to a sudden and temporary reduction in anthropogenic greenhouse gases and aerosol emissions (Le Quéré et al., 2020; Timmermann et al., 2020), as well as an improvement in the water quality (Lokhandwala and Gautam, 2020). Reduced human mobility during the pandemic significantly reduced the unintended disruptive effects on animal movement (Rutz et al., 2020). Pollution has been reduced on a global scale.(Muhammad et al., 2020). However, this direct impact of the pandemic-driven response on the global climate might be limited in the long term (Forster et al., 2020).

As the environmental impacts of the COVID-19 pandemic are still evolving, it is premature to conclude whether the pandemic will have an overall positive or negative effect overall on the environment. The indirect effects of COVID-19 on the environment include improvement in air quality, lower carbon emissions, clean beaches and reduced noise pollution. However, this is not a sustainable way to clean the environment. The negative side effects such as increased waste and reduction in recycling may last longer, and could be more challenging to manage (Zambrano-Monserrate et al., 2020). For instance, ubiquitous single-use face masks, surgical gloves and sanitizers have led to the generation of widespread medical waste and environmental pollution (Saadat et al., 2020). It has been estimated that 129 billion face masks and 65 billion gloves are used per month globally. Additionally, the mismanagement of personal protective equipment poses a risk to public health, as waste is a vector for coronavirus. Furthermore, the impact on ecosystems and organisms is also considerable (Prata et al., 2020). The polymer-based face mask waste is a potential source of microplastic pollution in the environment (Aragaw, 2020; Fadare and Okoffo, 2020).

The built environment also has the potential to affect an individual's health and well-being (Northridge et al., 2003). Considerations of the built environment are critical for building design, decision-making processes, and infection control mechanisms that are implemented by public administrators and individuals (Dietz et al., 2020). Urban density, which is defined as the intrinsic capacity of a city, is an important consideration when implementing preventive physical segregation policies such as lockdowns and social distancing in public transport, public spaces, and shared facilities (Lai et al., 2020). As there is a potential for the airborne transmission of COVID-19, the risk is high in indoor and crowded environments that do not have adequate ventilation, particularly in public buildings, workplaces, schools, and confined spaces (airplanes, passenger cars, and healthcare centers), where hand washing and social distancing might be insufficient to protect people from the virus-carrying respiratory microdroplets released into the air (Jayaweera et al., 2020; Morawska and Milton, 2020). A parallel reduction in airborne transmission using appropriate building engineering controls to improve indoor air quality, enhance particle filtration and air disinfection, and avoidance of air recirculation, would be effective strategies to limit the risk of infection indoors (Megahed and Ghoneim, 2020b; Morawska et al., 2020). Overall, COVID-19 poses a challenge at all levels in the built environment. To reduce the potential risks or to stop the coronavirus from spreading, it is needed to assess the current architecture and urbanism, and develop an antivirus-built environment (Megahed and Ghoneim, 2020a).

- Health

Vulnerable populations at higher risk of contracting COVID-19 include the elderly population, people with hypertension, diabetes or cardiovascular disease risk factors, and patients with respiratory diseases or conditions (Jiménez-Pavón et al., 2020). Unhealthy habits such as smoking might be associated with the severity and adverse outcomes of COVID-19 (Vardavas and Nikitara, 2020). One study reported an upward linear trend in the likelihood of COVID-19 hospitalization with increasing body mass index, suggesting that obesity and overweight are risk factors that increase the chances of contracting the infection (Hamer et al., 2020). Obesity, hypertension, diabetes mellitus and cardiovascular disease are also associated with a more severe course of COVID-19

(Stefan et al., 2020). Additionally, lifestyle changes such as household quarantine and lockdowns, could also induce negative health effects. For example, when children are out of school, they have lesser physical activity, longer screen time, irregular sleep patterns and less favorable diets, resulting in weight gain and a loss of cardiorespiratory fitness (Wang et al., 2020).

Furthermore, the interaction between the physical and psychological effects of COVID-19 can create a vicious circle. Related negative psychological effects include post-traumatic stress symptoms, confusion, and anger. Longer quarantine duration, fear of infection, frustration, boredom, inadequate supplies and information, financial loss, and stigma are stress factors during and after quarantine (Brooks et al., 2020). Concerns over psychosocial and mental health issues have also been raised. Mental health support is particularly needed for healthcare workers, childcare providers, children, the elderly, people with underlying health conditions, and people living in isolation. To deal with the challenges arising due to the COVID-19 pandemic, healthcare workers have had to make difficult decisions and work under extreme pressure that may increase the risk of injury and mental health problems (Greenberg et al., 2020). The pandemic has had a substantial impact on parents and children, and a national survey conducted in the United States reported that 27% of parents reported worsening mental health, and 14% reported worsening behavioral health of their children (Patrick et al., 2020). At this stage, it is critical to address issues such as domestic violence and child abuse (Galea et al., 2020).

Additionally, the pressing needs of individuals undergoing loss and grief have to be dealt with. Losses are associated with significant events and consequences, such as loss of loved ones, as well as major life changes such as job loss (Zhai and Du, 2020). Unemployment and unprecedented disruption of life and work can lead to distress and lower life satisfaction (Zhang et al., 2020). This may lead to an increase in suicidal ideation and behavior among individuals who are already facing mental health issues (Klomek, 2020).

3.2. *Guiding principles for environmental health research*

The challenges of the COVID-19 outbreak have brought forth a unique opportunity to re-emphasize, recharge, and jumpstart the vision of environmental health studies. Social systems, across the world, have been stalled and these should be reinstated through compassionate collaboration which would ensure that they are redesigned and rebuilt, post-COVID-19 era, in a sustainable manner (Robinson, 2020).

To initiate an exchange of ideas on the most pressing environmental health challenges and how these can be addressed through collaborative research between public health and social scientists, five key guiding principles for environmental health research have been proposed (Fig. 2). These include a transdisciplinary approach, embracing complexity and uncertainty, addressing vulnerability, boosting resilience, and sustainable development. As there is no globally applied working list and schedule, the focus would be on how to achieve better results for environmental health studies that are applicable worldwide.

- Transdisciplinary approach

The COVID-19 pandemic presents a transdisciplinary societal challenge. Effective responses to the complexity, emergence and uncertainty of the pandemic and the compound nature of social, environmental and health impacts require coordinated systemic thinking and actions (Lawrence, 2020).

It has become increasingly obvious that there are limitations in using isolated disciplines to understand and address complex issues triggered by the pandemic. Neglecting this multiplicity may lead to misleading conclusions and confusion concerning public responsibilities (Moradian et al., 2020). COVID-19 could be the accelerator of an expanded research paradigm transition toward a comprehensive, synthetic, and transdisciplinary science (Bontempi et al., 2020). Understanding environmental health problems requires expertise in different fields and a multidimensional perspective. It requires a transdisciplinary approach that transgresses traditional disciplinary boundaries, maps different methods and procedures of knowledge integration, and translates environmental health theory into practice. This could ensure policymakers, regulators, public health officials, and other stakeholders are better equipped to ameliorate the impact of future pandemics (Hoover et al., 2015).

Transdisciplinary research combines interdisciplinarity with a participatory approach. This integrates academic researchers from different disciplines and non-academic participants and leads to the development of integrated knowledge and theories based on science and society (Pohl, 2011). This promotes a holistic approach to understanding the complexity of existing environmental challenges, considers the diversity of life and scientific perceptions of problems, link abstracts and case-specific knowledge, and could lead to the creation of new knowledge and practices that would promote the common good (Cronin, 2008). This approach could also provide a systematic and comprehensive theoretical framework for the analysis of socio-environmental factors that influence human health and well-being (Rosenfield, 1992). Furthermore, it would shift the focus from traditional epistemology to problem-solving, from pre-given to emergent, and from universality to hybridity and contextuality (Klein, 2015). Transdisciplinary environmental health research guided by the goal of sustainable development can be a powerful tool for social change (Wahl and Baxter, 2008).

Compared to a multidisciplinary and interdisciplinary approach, the degree of integration and stakeholder involvement in a transdisciplinary approach would be relatively high (Mauser et al., 2013). Hence, this study addresses two characteristics of the transdisciplinary approach in environmental health studies: high integration and stakeholder

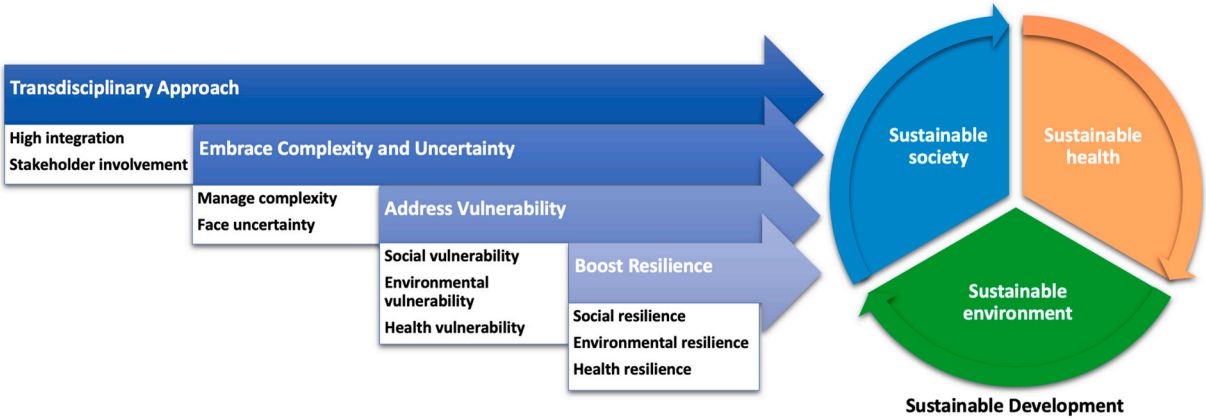

Fig. 2. Guiding principles for environmental health research.

involvement.

First, a transdisciplinary approach requires integrative problem-solving as opposed to analytic problem solving that is typically employed by reductionist approaches (Madni, 2010). A multidisciplinary approach attempts to sum up disciplinary knowledge, whereas an interdisciplinarity approach aims to integrate disciplines (Tress et al., 2005). Thus, different perspectives would merely lead to multidisciplinary work without meaningful integration (Repko and Szostak, 2020).

Integration is the core cognitive feature in the transdisciplinary research process (Jahn et al., 2012). This is an iterative process that involves ongoing reflection among scholars and practitioners representing diverse scientific disciplines and epistemologies, working together to develop novel conceptual and methodological approaches that would synthesize and extend disciplinary knowledge to identify innovative solutions for particular problems (Stokols et al., 2013). Transdisciplinary environmental health research requires knowledge integration from individual research areas, cooperation areas and fields, and identifying objectives and questions to develop a common vision. It involves the development of systems knowledge, target knowledge, and transformation knowledge (Pohl and Hadorn, 2007). To assist the knowledge integration process, some integration tools can be developed by transferring and adapting concepts between disciplines or creating new joint bridge concepts to merge disciplinary perspectives (Polk, 2015). Hence, "knowledge brokers" play a crucial role in building bridges between all participants alongside the processes, such as knowledge translation and community engagement (Pennell et al., 2013). Knowledge translation is often considered as a solution to improve the relevance and benefits of basic research (Archibald et al., 2018), and systems thinking plays a complementary role in leading the process. Tentative explanations are being formed as time progresses, and these assist in articulating elements of the system to aid understanding and consider interventions. An effective methodology to formulate systemic explanations is the use of illustrations (Coghlan, 2019). Thus, systems thinking explicitly provides a mechanism to integrate the societal, environmental, and health factors associated with sustainability (Cordell, 2010).

Second, a transdisciplinary approach is characterized by a multitude of stakeholders at all levels of the research process (Groβ and Stauffacher, 2014; Mauser et al., 2013). Stakeholder involvement crosses disciplinary boundaries, involves non-academic individuals and institutions, and it is critical for scientific knowledge development and practical knowledge application (Hadorn et al., 2008). In a response to the increasingly complex environmental health issues, there is a growing trend to conduct research in large intersectoral collaborative programs (Roux et al., 2010). Scientists need to strengthen partnerships and engage in collaborative efforts with a wide range of international, national, and subnational partners to address the pressing challenges at the global, national, and local levels to ensure a sustainable future (Gerding et al., 2020; Tong et al., 2010).

Transdisciplinary environmental health research would benefit from high levels of stakeholder involvement during the entire process. The category "intensity" of the involvement includes "information, consultation, collaboration, and empowerment" (Brandt et al., 2013). Stakeholder empowerment is a process in which stakeholders are given a voice, and this strategy has been successful in addressing several environmental health issues (Späth and Scolobig, 2017; Sprengel and Busch, 2011). For instance, a "bottom-up" program offered some special insights into the strengths, and challenges of stakeholder empowerment. In this community-based participatory research, professionals provided training and technical support to community members to enable them to conduct research on issues of their interest and concern (Wilderman et al., 2004). The effectiveness of stakeholder involvement is essential to gain new insights regarding environmental health research, generate a shared understanding of the research problems, and attain team objectives (Hall et al., 2012). It also requires a clear formulation of common goals among participants and the effective flow of knowledge to stimulate mutual learning. Importantly, active mentorship would ensure that all dimensions of complexity are considered, collaborative participation in building connections across disciplines is facilitated with an open-minded attitude, and collaborative work is undertaken to address complex environmental health problems (Matz et al., 2016).

- Embracing complexity and uncertainty

Environmental health problems are complex and accompanied by uncertainty. As compound social and natural systems are intrinsically impermanent and dynamic, complexity and uncertainty are recognized as two central characteristics of research (Méndez, 2015). The complexity of the dynamic processes and the interacting elements that govern the health status require scientists to adopt a comprehensive perspective and develop a holistic understanding of the system (Albrecht et al., 1998), which can assist them in structuring an integrated strategy to achieve sustainability.

COVID-19 is a striking example of a complex environmental health challenge with exceptionally unpredictable aspects, as the strain of the coronavirus has also been mutating and changing (Korber et al., 2020). Interspecies interactions, particularly those between humans, animals and pathogens, have drawn attention to the nonlinearity and unpredictability of environmental health concerns. These interactions are dynamic and have been evolving constantly and encompass interrelations within and across microbial populations, hosts and immune responses, and economic and political contexts (Senanayake and King, 2019). Unfortunately, many lives have been lost due to COVID-19. The all-pervading uncertainty that the pandemic has revealed are alarming. To begin, it is essential to accept that not everything is within our control, and that it is important to develop the capability to live humbly, harmoniously, reasonably, and healthily. Furthermore, having the courage to embrace complexity and face uncertainty with a positive attitude would lead to better preparedness, and would help decision-makers to respond more effectively in the complex and uncertain world.

- Addressing vulnerability

In environmental health research, vulnerability refers not only to the impact of exposure and sensitivity but also the adaptive capacity (Tong et al., 2010), which originates from the following factors: physical fragility or exposure, socio-economic fragility, and lack of resilience (De León and Carlos, 2006). Vulnerability can be assessed at various levels, including social, environmental, and health vulnerability (Cutter et al., 2003).

In low and middle-income countries, halting the spread of COVID-19 was much more challenging due to relatively weaker healthcare systems, limited resources, and the lower socio-economic status of the population. Attention has to be focused on the well-being of vulnerable populations, such as the homeless, indigenous, migrant, and imprisoned populations, people living with disabilities, and the elderly (Mesa et al., 2020). Furthermore, the inequities in risk are compounded by structural disparities in the society. For example, race, ethnicity, and income are associated with the risk of illness due to COVID-19 (Raifman and Raifman, 2020).

Socioeconomic status is closely linked to whether people are exposed to high-quality engagement activities, and the inequality of social capital could exacerbate social vulnerability and risk (Ge et al., 2019). It is essential to recognize pandemics and how societal, economic, and political determinants of health influence decision-making processes (Smith and Judd, 2020). Thus, investing in addressing social inequality can also be considered as an investment toward solving environmental health problems.

There is a link between health inequity and environmental degradation, whereby severe environmental health impacts have been

observed in the lowest-income households, and those who are already vulnerable to other deprivations (Leichenko and Silva, 2014). Human activities lead to increased environmental vulnerability. There is increasing evidence that the scale of the human enterprise has outstripped the resources available on the rapidly changing planet, and this has led to the disruption of the global climate system, widespread pollution, rapid biodiversity loss, reconfiguration of the biogeochemical cycle, pervasive changes in land use and land cover, and resource scarcity (Myers, 2017). This widespread ecosystem degradation will undoubtedly affect human health and well-being, and the potential impact of environmental vulnerability needs to be assessed in order to develop adaptation strategies, policies and measures to reduce the adverse impacts (Ebi et al., 2006).

- Boosting resilience

Resilience is a multi-dimensional process that implies the adaptive capacity available to deal with disturbances and changes in individual, institutional, and ecological systems across scales (Almedom, 2008). Vulnerability and resilience are reciprocal terms, which imply that a more vulnerable system would be less resilient, and a system is less vulnerable when it is more resilient (De León and Carlos, 2006). Many people have made psychological adjustments to deal with the COVID-19 outbreak (Chen and Bonanno, 2020), thus boosting their resilience has become an international priority. Strategies based on the recommendations of epidemiologists and public health experts from social and behavioral sciences can help in aligning human behavior (Van Bavel et al., 2020).

Humans are highly adaptable to environmental and social changes. From an environmental health perspective, resilience should be increased within the social, environmental and health systems, to ensure better response to and recovery from arising challenges (Kelley, 2013).

Social resilience is the capacity to cope with and adapt to environmental and social changes mediated through appropriate institutions. All aspects of demographic change, including migration, impact the social resilience of individuals and communities, as well as the sustainability of the underlying resource base (Adger et al., 2002). Resilience provides a useful framework to analyze the adaptation processes and identify appropriate policy responses (Nelson et al., 2007). For instance, regional economic resilience is determined based on a complex array of economic, institutional, political, and historical impacts (Tan et al., 2017a,b), and it should be observed from an evolutionary perspective (Tan et al., 2017a,b).

Environmental challenges require public health practitioners to acquire the latest knowledge on ecology, and advocate equality, new economics, and sustainable development (Middleton, 2008). Managing socio-ecological resilience is related to promoting health and well-being (Bunch et al., 2011). The characteristics of resilience encompass the wider social and economic determinants of public health. Important elements of health resilience include communication, learning, adaptation, risk awareness, and social capital. Therefore, community resilience is critical to ensure public health and for the purpose of emergency planning (Castleden et al., 2011).

Personal resilience is a critical domain of well-being (Bohman et al., 2017). It can be viewed as a defense mechanism that enables individuals to thrive during adversities. Improving personal resilience is considered as an important target for treatment and prophylaxis (Davydov et al., 2010). Meanwhile, there is a bidirectional relationship between systems-level and individual resilience. Effective interventions to enhance resilience must be based on the fact that resilience at the individual level is dependent on multiple layers of the society (Sippel et al., 2015). It is imperative to take into consideration the opinion of all those who have been physically or mentally affected by the pandemic and to ensure that research findings are translated into practice.

- Sustainable development

Sustainable development includes policies, projects, and investments that provide benefits without sacrificing social, environmental, and personal health in the long term (World Health Organization, 2020c). The concept of sustainability was first introduced in environmental studies; the concept is considered more holistically now and used in the context of a complex global system that incorporates diverse systems (Lo, 2015).

The declining condition of the natural environment has an impact on human health, and this has made the present healthcare achievements fragile. Furthermore, there are growing concerns that the contemporary patterns of economic development are unsustainable, and these have led to population growth, consumption increase, and excessive use of natural products and services (Dasgupta and Ehrlich, 2013). To address the challenging environmental health issues, it is necessary to ensure sustainability. Here, the importance of the integration of a sustainable society, environment and health is highlighted.

The COVID-19 pandemic has provided an opportunity to reduce the dependence and use of large volumes of energy and material (Cohen, 2020). Sustainable transformation, alongside actions that are farsighted and lead to long-term structural changes, is urgently needed. For instance, considering social justice, the process of shifting the socio-ecological systems toward sustainability is critical, and can have substantial social impacts and facilitate sustainable decision-making processes (Bennett et al., 2019). The politics of sustainable energy transitions are now at a critical juncture, in which the form and direction of state support for post-COVID-19 economic recovery are critical (Kuzemko et al., 2020). The pandemic has had a massive impact, and may fundamentally change the pathways and trajectories of sustainable energy development (Lo, 2020).

Furthermore, the reactions to the pandemic may provide useful insights regarding how to facilitate transformation to ensure sustainable supply and production (Sarkis et al., 2020). Human behavior plays a pivotal role in reducing damage and the magnitude of adverse environmental health consequences. By having a clear understanding of behavioral determinants, policymakers can harness an array of regulatory and incentive-based interventions to encourage sustainable lifestyles and encourage a shift in human habits and behavior, such as sustainable diet and consumption (Clonan and Holdsworth, 2012; Gilg et al., 2005; Hobson, 2001). Additionally, considering the rise of sustainable development and the emphasis placed on individual actions for the same, sustainable lifestyles can be framed in everyday practices with high effectiveness (Barr and Gilg, 2006). This can be encouraged through technological and social innovations (Mont et al., 2014). For example, the ongoing accumulation of knowledge and innovative activities aimed at addressing the COVID-19 pandemic indicate the evolution of innovation and technological exaptation in the context of crisis management (Ardito et al., 2021).

4. Discussion and policy implications

The significant impacts of the COVID-19 pandemic are intimately interconnected, as human health issues do not exist in isolation, nor are they separated from socio-ecological systems. The model (Fig. 3) summarizes the impacts of COVID-19, and also illustrates the importance of identifying the interdependence of social, environmental and health problems, as these issues interact with each other in complex, emergent and unpredictable ways.

For instance, an individual's lifestyle and behaviors influence the health of human beings, animals and ecosystems, which in turn, influence human biology, psychology and ecology. The prevalence and spread of a disease can be mediated through interactive biological, ecological, social as well as epidemiologic processes, and is directly or indirectly influenced by climate change (Chan et al., 1999). Human activities have put many species at risk. Deforestation and biodiversity loss are often considered to be the key drivers of zoonotic disease emergence (Poudel, 2020). During the COVID-19 outbreak, quarantine

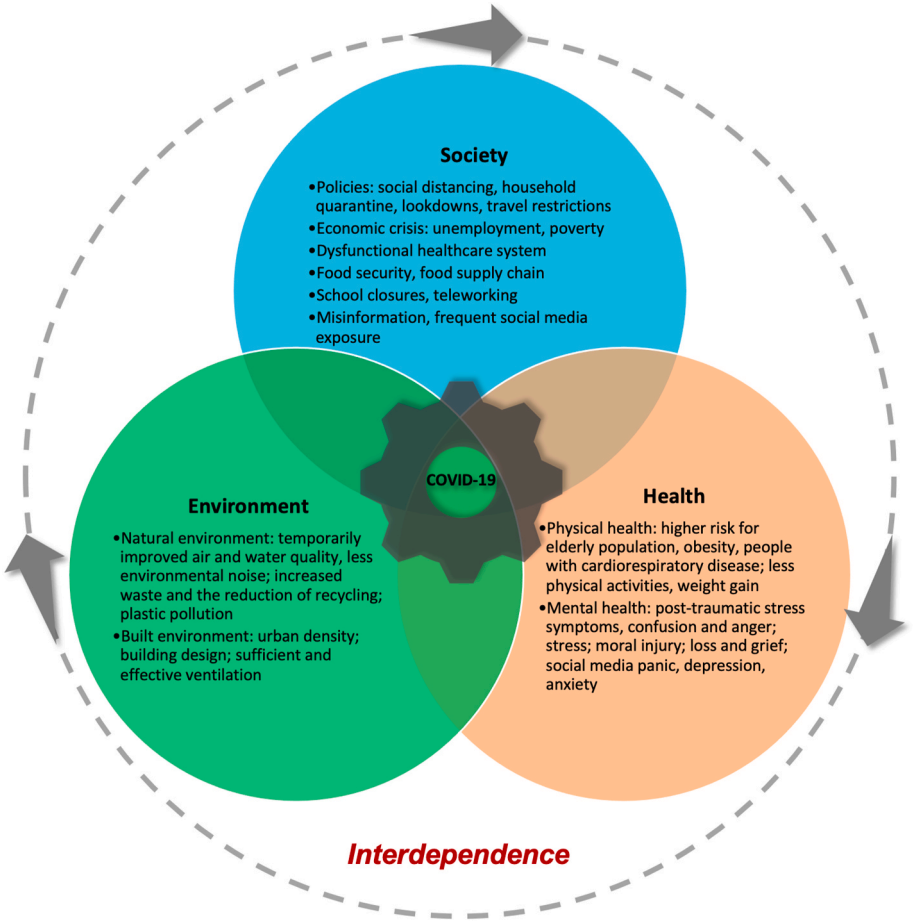

Fig. 3. Complex environmental health problems brought by COVID-19 and the interdependence of society, environment and health.

and lockdown measures led to a significant increase in low cloud coverage and relative humidity due to a decrease in travel and economic activities (Timmermann et al., 2020). Coccia (2021a) has demonstrated that geo-environmental factors, such as air pollution in cities, may accelerate the transmission and infection of COVID-19. Meanwhile, as residential space has become the main place where people could live, work, socialize, and so forth, poor housing has been associated with an increased risk of depressive symptoms. In other words, housing has become a key determinant of health. To investigate the effects of the built environment on mental health, it is necessary to consider various disciplines such as urban planning, public mental health, environmental health, epidemiology, and sociology (Amerio et al., 2020).

The COVID-19 pandemic has also indicated that environmental health problems can be effectively dealt with by changing human behavior and lifestyles. Although the positive impact of COVID-19 on the environment might be temporary, it can serve as an important indicator of how to reduce pollution, how best to share space with other species, and how the climate system will respond to the implementation of air pollution mitigation strategies on a long-term basis (El Zowalaty et al., 2020). It is time to reinvent lifestyles, forge a mutually beneficial coexistence with the environment, and reconsider the importance of a healthy ecosystem for the well-being of all (Rutz et al., 2020).

Subsequently, it is essential to recognize pandemics and how societal, economic and political determinants of health can influence decision making (Smith and Judd, 2020). The policy implications of this study are as follows: Lessons from the COVID-19 pandemic provide insights regarding visionary leadership that facilitates sustainable policy development based on environmental health science. Additionally, the proposed guiding principles for environmental health research can support the implementation of long-term and effective strategies to assist policymakers in coping with future crises similar to the global pandemic and to achieve effective sustainable transformation.

To accelerate progress toward achieving the SDGs, policymakers should ensure improved coordination to implement policies and apply integrated decisions based on international scientific cooperation (Coccia and Wang, 2016). Governmental projects on environmental health promotion can combine social and environmental factors and allow permanent sector policy integration (Holm et al., 2015). A participatory approach that involves the social, cultural, economic, ethnic, gender, and health impacts of all COVID-19 responses is urgently needed (Corburn et al., 2020). Rather than "keeping it simple", scientists are encouraged to embrace complexity and face uncertainty while conducting research and interacting with decision-makers (Winkler, 2016). There is also an urgent need to assess the vulnerability of environmental health issues from a transdisciplinary perspective, thereby identifying appropriate pre-emptive and adaptation strategies to minimize vulnerability and inequalities, and to promote sustainable development and equity. Additionally, transdisciplinary approaches and resilience objectives are being rapidly developed to inform and improve decision-making. Under the principle of addressing vulnerability and promoting resilience, there is a great opportunity to navigate socio-ecological transformations toward sustainability (Pereira et al., 2015). There is an overarching need to strengthen a "community of practices" to create and implement integrative policies with SDGs and their impacts on global health and socio-ecological system (Paula, 2018).

5. Conclusion

The decisions that the people and governments are taking now as a

reaction to the COVID-19 pandemic will shape the world for years to come. It is advisable to learn from the pandemic situation right now and move forward differently. Moreover, it is important to consider how we can be better prepared in the post-COVID-19 era. This could be a turning point in the state of the world where we bravely think beyond business as usual. The linear perspective forgets the interconnectedness of socio-ecological systems and how the systemic properties shape interactions, interdependencies, and interrelationships, whereas nexus planning emphasizes cross-sectoral sustainability and enhances resilience in the case of future shocks, and it could be adopted as a pathway toward sustainable environmental and human health (Nhamo and Ndlela, 2020). Scientists should consider thinking ahead to address the serious challenging questions and the profound impact on all aspects of society in a world that will transform greatly in the coming decades.

The COVID-19 vaccine is underway, and people are eager to return to "normal," but there is a dire need to redefine the meaning of "normal" or "the new normal" from a holistic perspective. In the past few decades, not much learning has stemmed from previous zoonotic diseases such as SARS, MERS, Avian flu, Ebola, and malaria (Poudel, 2020). Furthermore, as human beings neglected taking care of the earth, socio-ecological systems are facing multiple challenges due to human activities such as over-exploitation and wide-spread pollution of natural systems (Dorward, 2014). The pandemic presents a unique opportunity for us to act in solidarity and convert this crisis into an impetus to achieve the SDGs. It is important to reflect on what we have learned, reset our priorities, revisit the fundamental assumptions, accumulate knowledge to tackle future challenges, and start charting the path for a sustainable world (Pan and Zhang, 2020).

High organizational capacity to respond effectively to crises, such as the COVID-19 pandemic, is vital to deal with the subsequent socioeconomic influence (Coccia, 2021a). Urgent collective action at both the local and global levels is needed to mitigate the potentially devastating effects of COVID-19, and research needs to be conducted to enable a better understanding of these issues. The interaction between humans, animals and the environment has significant relevance in the occurrence of zoonotic diseases. This provides a base for discussion on the integrative approach and studies of diseases that go beyond discipline-specific science (Bonilla-Aldana et al., 2020).

The study of environmental health is based on separate silos of individual subjects and highlights the interdependence of the society, environment and health, at all scales. To support scientists in generating forward-looking contributions and translating the findings into practice, taking both pre-emptive and adaptive actions to protect the world from the consequences of the COVID-19 outbreak, this study suggests a set of guiding principles for environmental health studies, based on the identification of the transdisciplinary nature of these complex issues accompanied by uncertainty, to advocate addressing vulnerability, and boosting resilience for sustainable development.

The results and discussions of this study can serve as a catalyst and would require further research to develop a framework and guiding principles based on environmental health. There is a need for detailed studies regarding how to provide specific policy strategies and ensure effective management of crises, such as the COVID-19 pandemic, and establish sustainable pathways of growth in different environmental, health, and social backgrounds and societies. Thus, this study encourages future efforts in environmental health studies to provide evidence to substantiate comprehensive strategies and support long-term sustainable strategies.

In conclusion, this study draws on environmental health problems that have been caused by the COVID-19 pandemic and presents the guiding principles for future environmental health research. It is expected that environmental health studies will function as a vigorous tool to safeguard and improve the well-being of the society, environment and humans, as a whole. To ensure sustainable transformation, environmental health research will play a vital role.

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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