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REVIEW ARTICLE

Heterogeneous impacts of and vulnerabilities to the COVID-19 pandemic

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Abstract

Context The COVID-19 pandemic has impacted all sectors of society, with effects that have been acutelyexperienced at the local, national, regional, and global levels.

Objectives This study examined the heterogeneous impacts of and vulnerability to COVID-19 for promoting urban sustainability and resilience.

Methods We performed a scoping review on the basis of the relevant literature from the Web of Science and PubMed, and a national survey conducted among a total of 5,376 participants in early 2020. The survey adopted a repeated cross-sectional design to study changes in residents' risk perception of COVID-19 across the three stages (21–23 January, 27–28 February, and 24–27 March), using a snowball sampling method to recruit 2,144, 2,021, and 1,211 participants, respectively.

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Results This study revealed that the spatial, social, economic, and health impacts of COVID-19 have not been distributed evenly among populations, with specific individuals and communities more vulnerable than others. Among the determinants of these inequalities are socioeconomic status, housing arrangements, and working requirements, which influence the extent to which people can safely adhere to stay-at-home and social distancing policies and how they perceive risks. Additionally, racial/ethnic minorities face differing risks, in part because of socioeconomic factors but also because some groups experience higher shares of comorbidities. Moreover, overall, these risk factors are the healthcare systems meant to shield individuals and communities from pandemic impacts, which, however, have become increasingly taxed due to the sudden influx of patients and the resultant shortages of resources – including crucial personal protective equipment to minimize interpersonal transmission.

Conclusions Understanding the heterogeneous impacts of and vulnerability to COVID-19 could inform the design of environmentally sustainable and socially resilient cities, making them better equipped to encounter future epidemics. This study would help us identify more effective and equitable solutions to the ongoing challenges of the pandemic, promoting sustainability and resilience at multiple societal levels.

Keywords COVID-19 · Urban sustainability · Landscape sustainability science · Pandemic · Vulnerability · One Health

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Introduction

At the global policy level, the United Nations Sustainable Development Goals (SDGs) were adopted by member states of the United Nations in September 2015, aiming to guide the development of global sustainability in the decades ahead. However, the coronavirus disease 2019 (COVID-19), caused by SARS-CoV-2 and declared as a pandemic on 11 March 2020, has affected the progress towards the SDGs (Clemente-Suárez et al. 2022; Leal Filho et al. 2020; Nundy et al. 2021). On one hand, the dynamic, cross-boundary, multi-scale, and rapidly changing determinants of the COVID-19 pandemic are challenging traditional frameworks for understanding and protecting public health. On the other hand, ongoing global societal, environmental, and ecological changes—including rapid urbanization, population growth, increased global connectivity through trade and travel, climate change, widespread ecological modification (e.g., deforestation), political instability, and fragile public health systems—will yield epidemics that are more frequent, complex and difficult to prevent and contain (Bedford et al. 2019; Destoumieux-Garzón et al. 2022; Dobson et al. 2020), and epidemics in turn have an impact on the environment and ecology (Piquer-Rodriguez et al. 2023; Verma and Prakash 2020). However, these challenges provide opportunities to employ new technologies, cross-disciplinary science, and cross-sector efforts to interpret and protect the most vulnerable communities. To help design and promote environmentally and ecologically sustainable and socially resilient cities without being affected by future epidemics, we need to understand which aspects of the city and society have been influenced by the pandemic and how spatial design of cities and social systems have influenced the spread and vulnerability of the pandemic (Pamukcu-Albers et al. 2021).

The pandemic has called for a more robust and systematic response and a renewed and expanded social contract. Health at the center could be a lasting legacy of the pandemic caused by the spread of COVID-19. The heterogeneous impacts of COVID-19, which vary across populations and regions all over the world due to different vulnerabilities, have devastated global economy, intensified stress on political institutions, and exacerbated spatial and social inequalities and environmental problems. Disciplines spanning epidemiology, ecology, environmental

sciences, biomedical sciences, economics, international relations, logistics, behavioral sciences, and crisis management must be urgently integrated to marshal the requisite global responses (Azevedo et al. 2020). Meanwhile, future pandemic prevention and preparedness efforts will likewise require an expansive and progressive approach encompassing ecosystems, wildlife disease surveillance, agricultural practices, dietary trends, and cultural traditions. A One Health perspective is needed that integrates traditional domains of knowledge, governance, and sectors to address the challenges posed by COVID-19 and future pandemic threats. Our perception and understanding of epidemics must evolve from crisis response during discrete outbreaks to an effective system of public health that integrates lessons learned from previous potential pandemics. To ensure that we can manage any future outbreaks, one must thoroughly understand the causes and effects of the pandemic. The perspectives of each economic sector are equally essential to chime in towards promoting environmentally and ecologically sustainable development goals, where we can all work towards achieving urban sustainability (Holzer and Orenstein 2023).

The emerged landscape sustainability science offers a new perspective for understanding heterogeneous impacts of and vulnerabilities to COVID-19. For example, landscape sustainability science proposes cross-disciplinary approaches to understand and promote the long-term coexistence of social, economic, and environmental systems within landscapes, including landscape resilience, landscape governance, and regional biophysical human-nature connectedness (Wu 2021). More specifically, landscape sustainability science provides frameworks for analyzing how COVID-19 affects various aspects of landscapes, for example, how different components of landscapes (e.g., ecosystems, communities, infrastructure) may respond and adapt to the impacts of COVID-19 could be examined; the effectiveness of governance structures and policies in managing the COVID-19's effects on landscapes could be investigated, such as issues of equity (e.g., regarding discrimination, education), resource allocation (e.g., supply chain, energy production and consumption), and decision-making processes.

Based on the existing literature and a national survey we have carried out, we adopted the framework of landscape sustainability science to understand heterogeneous impacts of and vulnerability to COVID-19 across spatial, social, economic, and health dimensions. By examining spatial inequalities, social inequalities, and the effectiveness of governance, we examined how COVID-19 disrupted sustainability and how human-environment systems—primarily ecosystems, human communities, infrastructure, and governance—responded to and adapted to these challenges. To make this review manageable and concentrated, we focused primarily on China and supplemented with findings from other parts of the world, whenever necessary. The findings of this review would help us better understand urban sustainability and realign with the SDGs.

Impacts of COVID-19

Pandemics rarely affect populations uniformly. The Black Death in the fourteenth century reduced the global population by one third, with the highest number of deaths observed among the poorest regions (Duncan and Scott 2005). Seven centuries on—with a global gross domestic product (GDP) of almost US$100 trillion—is our world adequately resourced to prevent another pandemic? Current evidence from COVID-19 suggests otherwise (Ahmed et al. 2020).

Othering and structural inequalities

Creating societies that embrace inclusivity, reject discrimination, and work towards reducing inequalities is a recurring focus throughout all the SDGs (Hackl 2018). These goals acknowledge a strong interconnection between urban sustainability, ethical values, and the promotion of fairness and justice (Holzer and Orenstein 2023). However, throughout history, infectious diseases have been associated with the social practice of "othering", in which certain groups are stigmatized as being harmfully foreign (White 2020). Pandemics have historically stimulated nativist sentiment, providing populist politicians with openings to advance a xenophobic agenda. One of the most well-known historical examples of this is the rise in anti-Semitism during outbreaks of the bubonic plague in Europe during the medieval era (Cohn 2007). COVID-19 has been an unfortunate occasion for such social fracturing, including the spread of

discriminatory actions and policies and the marginalization of minority groups.

Rather than being a social equalizer, forcing people to recognize the common risks arising from ordinary humanity, COVID-19 has elicited racially harmful policy responses that have disproportionately affected people of color and migrants (Lopez et al. 2021). These include being over-represented in lower socioeconomic groups, having limited healthcare access, or working in high-risk jobs. Moreover, such ethnic groups as African American, Hispanic, and Latin American face higher discrimination due to their living conditions. It is found that these ethnic groups are more likely to live in closely knitted communities, both socially and spatially, than the other races (Webb Hooper et al. 2020). Furthermore, the link between a tightly knit community and crowded housing conditions has brought about household assessments whereby these groups are more likely to work in service and transportation jobs. Due to the nature of jobs as having close contact with others, these communities are discriminated against their race and jobs, which are seen to only be taken up by poor people (Lopez et al. 2021; Webb Hooper et al. 2020).

Moreover, social distancing policies are a privilege that only the rich can uphold; the poor live in tightly knitted homes and communities, which adds to the racial discrimination (Abedi et al. 2021). This rising discrimination compounds the risks faced by minority groups already suffering from high rates of comorbidities (e.g., hypertension in African American populations (Go et al. 2014) and diabetes in people with South Asian backgrounds (Unnikrishnan et al. 2018)). Furthermore, migrants, particularly those without documentation, often avoid hospitals for fear of identification and deportation, as has been observed during COVID-19 (Neil 2020).

Economic repercussions

The most recent estimates indicate that COVID-19 could cost the global economy more than US$10 trillion (IMF 2020), although considerable uncertainty exists concerning the projected spatial extent of the virus and the efficacy of the various policy responses (Ahmed et al. 2020). The severity of the impact on the global economy is primarily due to the implementation of quarantines, social distancing, and other "lockdown" policies, which have caused a significant drop in production, consumption, trade, and investment across the world (Wang and Wu 2021). In Malaysia, the first lockdown led to a decline in the transportation of shipping lines (by 25.5% in May 2020), where the trade and supply lines are crucial for imports and exports of the country (Menhat et al. 2021). Due to the closure in the port, trade led to a standstill where many perishables are left to rot in the port. The lockdown has no doubt caused numerous problems on a national scale, but in the bigger picture, it affects the global economy where several countries have to rely on one country's exports (Amul et al. 2022). According to the latest estimates from the International Monetary Fund, global GDP, the primary indicator of macroeconomic conditions, is expected to fall 3% in 2020, the steepest drop since the Great Depression more than 70 years ago (IMF 2020). The impacts will be widespread, with advanced economies (e.g., the US, Japan, and the European Union) likely to see the steepest falls in GDP. Since such records have been kept for the first time, emerging markets are also expected to collectively experience contraction (IMF 2020).

After lockdowns were enacted across most states in the US, the resultant fall in retail sales was 14.7% in April 2020 (IMF 2020). Estimations of the US economy since the start of COVID-19 until a prediction of stagnation, possibly up till 2030, would yield an astronomical cost 90% of the current US GDP. This value is by far greater than the economic loss incurred during the US war on terror campaign in the middle east, up until the recent withdrawal from Afghanistan (Cutler and Summers 2020). The European Union had already undergone nearly a decade of economic stagnation due to the 2009–2010 financial/Eurozone crisis. They too underwent an estimated fall in the retail of 3.26 billion pounds ($4.24 billion) in the six weeks to 20 April 2020 (IMF 2020). In China, the relatively quick containment of disease spread allowed the country to begin "reopening" (i.e., allowing workers to return to factories, offices, and other places of work) by April 2020. Nonetheless, first-quarter GDP dropped by 6.5%—the first time the country experienced economic contraction since quarterly data started to be kept in the early 1990s (Chen et al. 2021b; Cutler and Summers 2020).

The declining consumer demand due to stay-at-home orders led to a significant increase in

unemployment across many sectors. In the US, which leads the world in the number of infections and fatalities, unemployment claims totaled 20.5 million in April 2020 alone (raising the unemployment rate to 14.7%)—by far the most significant number ever recorded (Statistics 2020). In China, unemployment also ticked up to 6% in April 2020, only a modest increase in the international context but a significant drawback for an economy that had been experiencing three decades of continuous, high-speed growth. In the European Union, unemployment rates were also more modest than in the US due to more extensive welfare protections (preventing layoffs through furloughs and income support for laid-off workers).

The impact on international trade has also been significant. Over the first quarter of 2020, the international trade of goods and commodities fell by 5%, and the number is expected to decline further by 27% in the second quarter—another record-setting drop in a crucial economic indicator (IMF 2020). Additionally, the pandemic-induced surge in demand for ventilators and personal protective equipment (PPE), concentrated in China, exposed the potential problems of current supply-chain dynamics. The "just-in-time" supply chains established over the previous decades, in which efficiency has been prioritized over distributional balance and system resilience, conflict with the perceived national security interests of many countries in crises. Consequently, analysts have predicted that global supply chains could undergo structural changes post-pandemic with a more significant localization of production, especially for those goods and commodities deemed sensitive to national security (Jim et al. 2020).

The economic aftermath of the pandemic will present profound obstacles—perhaps most significantly in terms of the financial burden and deflationary pressures, leading to lower trend growth in GDP and persistent unemployment problems. Although the global economy is projected to experience rebound growth of close to 6% in 2021, it will likely take years for macroeconomic conditions in most countries to stabilize and for income and employment to return to pre-crisis levels. Additionally, if international trade fracturing and associated geopolitical tensions worsen, so will downward pressures on production, consumption, and investment. During the crisis, the enormous debts accrued by governments as they attempted to mitigate unemployment, prevent commercial bankruptcies, and inject purchasing power into households will also act as a drag on economic recovery (Martin 2020a). For instance, it is projected that US gross federal debt is likely to reach 125% of its GDP in 2021 – which is more significant than during the Second World War (IMF 2020).

Environmental impacts

The long duration of COVID-19 has brought negative environmental and ecological impacts in multiple aspects, varying by type of human impact. For instance, in Europe, despite the reduction of delicate particulate matters and NOx emissions during COVID-19 (by about 8% and 53%, respectively), the concentration of ozone has increased by about 17%, which may further increase the human mortality rate and decrease the production of crops (Sicard et al. 2020). Also, the increasing use of PPEs (e.g., medical masks and gloves) in daily life and disposal of other single-use plastics has substantially increased waste pollution, such as an estimated monthly use of 129 billion face masks and 65 billion gloves globally during the pandemic (Prata et al. 2020). Such accumulation of plastic waste has put extra pressure on regular waste management practices. For example, plastic wastes discarded in animals' natural habitats, both land, and ocean, could be mistakenly eaten by animals, leading to their death (Adyel 2020).

It has been reported that deaths in marine life are more common now, with the addition of face masks as discarded waste in the open ocean (Thompson et al. 2020). Already harmed wildlife, such as the sea turtle that consumes jellyfish, is at a higher risk of being harmed with the inclusion of face masks. Due to the nature where plastic bags flow in water, the face mask, too, resembles a jellyfish; while this is only one example, accidental consumption by wildlife is at a higher rate than before (Dharmaraj et al. 2021; Patrício Silva et al. 2021). Additionally, when dumped into the environment, face masks would break down through chemical and physical processes; as a result, microplastics are formed whereby they harm both water and soil (Tesfaldet and Ndeh 2022). This environmental pollution is another point to note where the global food chain is harmed, starting from the phytoplankton that ingests these microplastics, then the larger zooplankton, fish, and crustaceans consume them. Subsequently, these marine lives are

then consumed by humans, and thus microplastics are ingested—leading to health risks (De-la-Torre et al. 2021; Torres-Agullo et al. 2021).

The concentration of disinfectants in domestic wastewater has also increased, which may generate toxic by-products; discharging wastewater polluted with excessive disinfectants and their by-products into surface water through drainage pipe networks can exacerbate existing environmental and ecological problems to levels that are not yet being recognized (Chu et al. 2021; Li et al. 2021).

Food security

Economic and social shocks can have significant consequences for food security and undernutrition (Studdert et al. 2001; Brinkman et al. 2009; Yngve et al. 2009; Vilar-Compte et al. 2015; Loopstra et al. 2016), and increasing food security and landscape multifunctionality could contribute to urban sustainability (Clark and Nicholas 2013). COVID-19 has placed unprecedented strains on global food supply chains. The highly integrated global food system is vulnerable to instability, leading to global food price volatility and uneven regional resilience to price spikes (Falkendal et al. 2021). Supply chains are complex and often stretch across international borders, involving the trade of agricultural inputs, widely distributed farming activities, storage and processing in large-scale facilities, and transportation and retail of food products to consumers. As agriculture dwindles in many low and middle-income countries, so does their food security. The types of products that they grow include wheat, maize, and rice, all of which are primary food sources that high-income countries require for the industry needs. Consequently, the steps and processes are backed up from raw materials to primary consumers. In China, as just one example, soybeans imported from the US may be processed in one province—and the processing plant itself may be a subsidiary or jointly owned by an international corporation—used as poultry feed in another province, and the poultry exported to South Korea (Hawkes et al. 2009; Sun et al. 2018; Haque et al. 2021).

Short-term shocks to the food supply chain during COVID-19 have been significant, including panic buying or stockpiling, shifting patterns of food purchasing from restaurants and schools to food markets, labor shortages stemming from infections among domestic workers and policies targeting migrant workers, and difficulties in transporting agricultural and food products due to movement and trade restrictions (Hobbs 2020). In China, these shocks have led to higher prices for many types of food, especially fresh produce and animal products such as meat, fish, and eggs (Dou et al. 2020). Whether and how these short-term impacts will translate to long-term effects is uncertain, but these trends are intersecting with global economic forces that are disproportionately impacting groups that are already disadvantaged concerning nutrition and health (Béné et al. 2021).

The agriculture sector in China has experienced labor and input supply challenges stemming from quarantine policies. Restrictions on travel and movement led to shortages in labor supply, fertilizers, pesticides, and the inability of farmers to move agricultural products to storage, slaughterhouse, and markets (Martin 2020b; Antwi et al. 2021). Early data suggest that rural areas experienced drastically higher unemployment rates and reduced income than urban areas during the lockdown, resulting in undernutrition (Kartari et al. 2021). Higher food prices across the country increased concern for and experience of food insecurity in many areas (Dou et al. 2020).

Reductions in international food trade exacerbated domestic supply issues, particularly for soybeans, which are critical for animal feed and cooking oil production in China, and pork, following steep declines in the domestic supply in 2019 due to the African swine fever epidemic (Thukral et al. 2020; You et al. 2021). Countries, including Russia, Kazakhstan, and Cambodia, have imposed export bans on their staple crops to protect domestic supplies. Although not currently a threat to China's ability to import sufficient crops, such actions can escalate global trade crises, cause global spikes in food prices, and further destabilize the supply chains that countries rely upon to meet population nutritional needs (Zhao et al. 2021). China has thus far mitigated the effects of the pandemic on the food trade by increasing market access and easing customs and quarantine procedures for imports (Martin 2020b). Looking ahead, China is preparing for further international supply disruptions by increasing national stores of essential crops and instituting policies to increase domestic agricultural production (Lu et al. 2022).

Energy production and consumption

The comprehensiveness of pandemic-induced lockdown regimes across the world has had significant implications for energy use. Indeed, countries that have been placed under total lockdown—i.e., restrictions on travel and movement and stay-at-home orders for all non-essential workers—have experienced an average decline in energy demand of approximately 25% per week, with an estimated 18% decline for countries in partial lockdown (Dawn et al. 2022). Daily data until 14 April 2020 for 30 countries that constitute over two-thirds of the global energy demand show that this demand depression has been a function of the duration and stringency of lockdowns (Lazo et al. 2022). Global energy demand fell by 3.8% in the first quarter of 2020, with the most significant drop occurring in March as confinement measures began to be enforced in Europe, North America, and elsewhere (Gollakota and Shu 2023).

Coal and oil, the most widely used fossil fuels, and transportation and industry lifeblood saw unprecedented declines. Global coal demand in the first quarter of 2020 dropped by almost 8% compared with the first quarter of 2019 (Koca and Genç 2020). There were three primary drivers. First, China's coal-based economy (coal accounted for 57.7% of the national energy mix in 2019) was the first to be stricken by COVID-19, going into complete lockdown through most of the first quarter (Tu 2020). Second, the lower demand for coal was exacerbated by concomitant low gas prices and the continued growth of renewable energy (Corbet et al. 2020). Finally, mild weather in China and many other countries meant decreased demand for coal during a period where coal-fired heating is usually standard. Even in Europe, where lockdown measures were enacted in a more fragmented fashion across countries, coal-based power generation fell by 37 GW in April 2020 (or a drop of 12% compared to the 5 previous years) (Werth et al. 2021).

The oil demand also experienced a precipitous fall of nearly 5% in the first quarter of 2020 (Gollakota and Shu 2023). This fall was primarily due to the curtailment of automobile use and low commercial aviation traffic, accounting for nearly 60% of the global oil demand (Abu-Rayash and Dincer 2020; IEA 2020). By the end of March 2020, global road transport activity was almost 50% below the 2019 average, and aviation was 60% below (IEA 2020). In Europe alone, oil-based power generation was reduced by approximately one-third (IEA 2020). The impact of the pandemic on demand for natural gas, the third primary fossil fuel, was more moderate, inducing a drop of around 2%, as natural gas-based economies such as Russia and Germany were not strongly affected in the first quarter of 2020 (Alam et al. 2023).

Like the demand for transportation fuels, the electricity demand has fallen significantly. Electricity demand has been depressed by 20% or more during periods of total lockdown in several major economies, with the demand curve through much of the first and second quarters of 2020 resembling that of a prolonged Sunday when usage is typically lowest (IEA 2020). As a result of lockdown-induced lifestyle and job requirement changes, people have spent much more time at home, increasing the residential load demand for electricity. However, this was insufficient to balance the substantial, concomitant decreases in commercial and industrial loads.

Demand fell for all sources of electricity except renewable energy, which was the only energy source that posted growth in demand in 2020, driven by larger installed capacity and priority dispatch, or the obligation of operators to transmit energy from renewable sources ahead of other sources (Strielkowski et al. 2021). Despite a fall in overall electricity consumption, the demand for renewable energy increased by about 1.5% in the first quarter of 2020, primarily as a result of wind and solar projects completed over the previous year, but also due to the preferential access to power grids under "priority dispatch" regulations in most major economies (IEA 2020). Renewables are expected to be the only energy source that will grow in 2020, although the projected growth rate of 5% will be lower than in previous years (IEA 2020).

Education

The pandemic has severely impacted education and associated lockdown measures like other social and economic aspects. In response to COVID-19, at least 107 countries had implemented national school closures as of 18 March 2020. However, analysis of data from the 2002 to 2003 SARS outbreak in mainland China, Hong Kong, and Singapore suggested that school closures do not necessarily contribute to

the control of disease spread, with modeling studies producing conflicting results (Viner et al. 2020). Recent modeling studies of COVID-19 have predicted that school closures alone could only prevent 2–4% of deaths, which, while not insignificant (especially on humanitarian grounds), was not as systematically effective as other social distancing policies. Other, less disruptive social distancing interventions in schools merit further consideration if restrictive social distancing policies are implemented for long periods (Viner et al. 2020).

As with work-from-home regimens sustained by digital networks, "online classrooms" have become increasingly widespread in many countries in response to pandemic lockdowns. Students can access important documents and lectures through online platforms in most cases. This "learn-from-home" approach may become increasingly normalized even after the pandemic has abated and students return to their physical classrooms. A significant limitation is that socioeconomic inequalities mean that not all schoolchildren have reliable internet access at home, even in affluent countries. These issues of differential accessibility and, consequently, an opportunity could have long-term impacts on educational attainment (Gecaite-Stonciene et al. 2021; Neuwirth et al. 2021).

Vulnerability to COVID-19

COVID-19 has revealed sharp health disparities and had more significant impacts on highly vulnerable regions and populations, including those who were disproportionally exposed and highly susceptible to severe COVID-19 infection. Vulnerability describes the susceptibility of a given population, system, or region to harm from exposure to the hazard and directly affects the ability to prepare for, respond to, and recover from hazard and disasters (Adger 2006; Cutter et al. 2009). It is clear that there exists significant dynamic vulnerability to COVID-19. That is, a region or person not considered vulnerable at the outset of a pandemic can become vulnerable depending on the policy response. Differences in socioeconomic, demographic, and spatial contexts, such as income and access to medical resources, race/ethnicity, and proximity to outbreak epicenters, result in different levels of exposure to the pandemic and capacity to treat infections.

Spatial inequalities

The impact of COVID-19 on any region is not spatially uniform, with geographical factors profoundly influencing individuals' risks through various channels (Yang et al. 2021a; Huang et al. 2022; Zhang et al. 2022b). Economically disadvantaged places often lack sufficient spatial access to healthcare services, which could worsen during public health emergencies when access to testing is crucial (Yang et al. 2021b; Jia et al. 2022). For example, rural areas and low-income urban neighborhoods frequently face shortages of healthcare providers including different levels of healthcare facilities (e.g., hospitals, primary healthcare centers, pharmacies), resulting in delayed diagnosis and treatment (Pirisi 2000). It is particularly true in China, where some municipalities and provinces, such as Shanghai, Beijing, and Tianjin, generally have greater proximity to the nearest primary healthcare centers; in contrast, regions such as Tibet, Guizhou, and Guangxi, have lower proximity to the nearest primary healthcare centers (Jia et al. 2022). Also, rural hospitals in the United States are often underresourced and face significant financial challenges, affecting their ability to respond to COVID-19 effectively (Mueller et al. 2021).

Additionally, individuals in remote areas or underserved urban communities may lack access to reliable sources of information, making them more susceptible to misinformation and hence disregard health advisories from governments. For example, during COVID-19, village-level data from Sichuan Province of China revealed that households with lower socioeconomic status were more vulnerable to the pandemic, highlighting disparities in the access to resources and resilience capacities (Ur Rahman et al. 2021). Rural populations in the United States faced challenges in accessing reliable Internet services, which has impeded them to receive timely and accurate public health information (Bekemeier et al. 2023). The uneven spatial distribution of healthcare resources and infrastructure could therefore create substantial disparities in health outcomes during epidemics; unequal spatial access to healthcare and testing facilities, often exacerbated by socioeconomic factors, could lead to higher infection rates and poorer health outcomes in disadvantaged areas (Rocha et al. 2021).

In addition to the access to healthcare services and information sources, population outflows and urban resilience also exhibit significant spatial inequalities. For instance, population outflows from the outbreak regions of COVID-19, posed elevated risks to destination regions, highlighting how spatial dynamics and mobility patterns exacerbated inequalities (Qiu et al. 2020). In China, urban resilience is higher in eastern regions, urban agglomerations, and larger cities than in central and western regions, non-urban agglomerations, and smaller cities (Wang et al. 2023). This uneven distribution of resilience underscores disparities in the infrastructure and economic development. Furthermore, the factors impeding the improvement of urban resilience have evolved over time, such as economic status and education, leading to more severe spatial inequalities.

Social inequalities

Intertwined with spatial inequalities, social inequalities further exacerbated the risks and impacts of COVID-19. Many workers in the lowest-wage sectors (e.g., food and delivery systems) are deemed "essential" and continue to risk their lives to keep society functioning. Major supermarket chains have reported employee deaths, and the soaring rates of infection in meatpacking plants reveal an industry-wide lack of attention to the safety of their workforces, who have had to strike for paid sick leave, sanitization procedures, and basic protections like hand sanitizers. In the US, for instance, people of color (e.g., African and Latin Americans) are over-represented in those sectors, thus magnifying the risk for those in already vulnerable socioeconomic groups (Devakumar et al. 2020). In pandemic conditions, those who perform this "essential" work and remain unprotected physically, socially, environmentally, and financially face elevated risks of infection and mortality rates.

During the COVID-19 lockdown, school closure and the transition to online learning exacerbated the existing education gaps, particularly for children from low-income families who had limited access to digital devices and reliable Internet service (Cruz 2021). This is especially pronounced in rural areas of China, where inadequate infrastructure and resources have left many students at a disadvantage, further entrenching long-term educational inequalities (Zamir and Wang 2023).

Socioeconomic status played a pivotal role in shaping vulnerability to COVID-19. Lower-income households often lack the financial flexibility to stockpile supplies or access private healthcare, leaving them more exposed to disruptions during the pandemic (Li et al. 2023). Additionally, limited financial resources constrain individuals' ability to seek timely medical treatments or adopt preventive measures, such as purchasing personal protective equipment or maintaining proper hygiene (Cheng et al. 2021). Furthermore, socioeconomic status influenced mental health during COVID-19. Financial stress and job insecurity were significantly correlated with the increased anxiety and depression among the disadvantaged groups (Brown et al. 2022). These challenges underscore the need for tailored measures of social protection to mitigate the impacts of socioeconomic status-related disparities during public health emergencies.

Disparate health outcomes can reflect different comorbidities, behavior sets, and other factors determined by broader social conditions. The experiences of ethnic minority communities in western countries are illustrative. There have been increased morbidities and mortalities in Black and other minority groups in previous pandemics; especially during COVID-19 in the US and the UK (Zhao et al. 2015; Richardson et al. 2020). Furthermore, in the UK, it has been found that South Asians have higher rates of some comorbidities (e.g., diabetes, hypertension, cardiovascular diseases) compared to Europeans. These comorbidities have been associated with severe disease and mortality in COVID-19 (Tillin et al. 2013). Moreover, ethnicity can be a factor in spreading viruses through its association with socioeconomic status. However, it may also interact with cultural differences such as specific health-seeking behaviors and intergenerational cohabitation. Furthermore, it may be challenging to disentangle given the complexity of social dynamics and the interactions (Pareek et al. 2020). Understanding the roles played by social inequalities in pandemic risk will require studies quantifying absolute risks and outcomes in these disadvantaged groups, as well as qualitative studies of behaviors and responses to pandemic control messages (Pareek et al. 2020).

Housing and living conditions

The ability to engage in physical distancing is sensitive to one's housing conditions (e.g., whether to live in a detached home or an apartment block), health status (e.g., whether to need regular hospital visits), the population density of the surrounding neighborhood, and other environmental conditions (Yang et al. 2021d). The primary strategies recommended for the prevention of COVID-19—in particular social distancing and frequent handwashing—may be difficult or impossible to follow for those in crowded living conditions or with inadequate access to clean water (Chia et al. 2021). For example, incarcerated persons may encounter unavoidable close contact in densely populated, poorly ventilated, and unsanitary facilities, with restricted movement and limited medical care (Kinner et al. 2020). Practical challenges of physical distancing and quarantining are abundant for those without shelter and populations in urban slums, where people may congregate in informal settlements, and where there is shelter, multiple people may share a room, and multiple households rely on the same limited infrastructure. Enforcement of lockdowns has been accompanied by an increase in the authoritarian behavior of the police, with the poor experiencing brutal civil rights violations as documented in India, Nigeria, Kenya, South Africa, and elsewhere (Cash and Patel 2020). In sharp contrast, lockdowns can impose little more than an inconvenience for the affluent members of such societies (Cash and Patel 2020). Policies to control the pandemic and restore stability and prosperity must explicitly account for these differences in vulnerability, lest they create or exacerbate social injustice.

Rural settings also face infectious disease risks, although these may arise from different factors. For instance, rural areas tend to have fewer health care resources and may experience increased risk if there is a flight from urban areas due to pandemic concerns. In India, for instance, lockdown measures in cities prompted tens of millions of migrant workers to return to their village homes, potentially spreading COVID-19 along the way and into vulnerable rural communities. Effective pandemic containment policies must therefore address the potential risks in rural and peri-urban areas in addition to those in urban centers (Ranscombe 2020).

The ability to access nature within one's living environment serves as a mitigating factor in coping with the stressors and impacts of COVID-19 on mental health. For instance, research has demonstrated that contact with nature—whether through views of green spaces or the presence of plants in the home—can alleviate anxiety, depression, and other psychological stressors associated with confinement and isolation during the pandemic (Garrido-Cumbrera et al. 2023). Similarly, having indoor plants has been linked to one's improved mood and reduced stress during lockdown periods, underscoring the therapeutic value of green environments in homes (Pérez-Urrestarazu et al. 2021). An increasing body of evidence reveals that contact with blue-green spaces may positively affect mental health and aid individuals in coping more effectively with lockdown measures (Pouso et al. 2021; Garrido-Cumbrera et al. 2022; Grace et al. 2024). The importance of incorporating natural elements into housing and urban planning is evident, as green space could not only improve physical well-being, but also enhance mental resilience during crises like COVID-19. Policies aimed at improving housing conditions must therefore consider the integration of natural space to promote both physical and psychological health.

Health systems

Infectious disease reporting, an essential component of a health system, is generally subject to inherent time lags and can therefore have limited value for identifying early risks and issuing warnings prior to public health emergencies. Although most countries have set guidelines and defined procedures to counter the spread of infectious diseases such as COVID-19, most have been ill-prepared to deal with the pandemic's abruptness, scale, and pace. Improving protocols and infrastructure for how public health professionals should initiate work, assess risk, release information, and investigate and manage infected cases in the event of a major crisis such as COVID-19 should be a priority for future public health policy. For example, the national intelligent syndromic surveillance system (NISSS) has been considered necessary in the era of infodemiology to detect early and tackle the epidemic quickly and forecast the outbreak accurately and robustly at the early stage of the epidemic (Jia and Yang 2020a, b).

The NISSS expects to identify early risks based on information about patients' symptoms (e.g., cough, fever, shortness of breath) during the early phases of illness and surrogate data indicative of early illness (e.g., school or work absenteeism data, unexpected avian deaths). Identifying early risks would first involve a central data bank integrating multiple data sources. Then, an artificial intelligence-based analytical core to support decision-making. Furthermore, a location-based service system that enables real-time and geo-tagged communication between public health officials/professionals and citizens is expected to be implemented. By informing multiple stakeholders (e.g., health officials, hospitals, citizens), immediate actions to curb the epidemic at the first moment are possible (Yang et al. 2021c).

In China, although the absolute level of public health investment has grown, its proportion over the total health expenditure has decreased since 2009. The country has developed large-scale infectious disease surveillance and reporting system. However, a higher proportion of public health investment (including programs that target infectious disease risks) would likely have improved the country's detection of and response to the recent pandemic (Fig. 1).

In the ongoing pandemic, frontline containment efforts are being carried out by medical professionals in hospitals, clinics, and temporary treatment locations (Chen et al. 2020d; Li et al. 2020b). These individuals are at high risk of infection and have experienced substantially elevated COVID-19 incidence rates (Pan et al. 2020). For instance, China's National Health Commission reported that more than 3300 healthcare workers had been infected by early March 2020, with at least 22 deaths; in Italy, 20% of responding healthcare workers became infected, also attended by a relatively high number of deaths (Lo and De Angelis 2020). As the pandemic worsened, access to PPE for health workers became a key concern, although it can be supplemented by storage, deployment, and expansion of production capacity. While certain countries (e.g., China, which is also the world's leading producer of PPE) had readier access than other countries globally—numerous others affected by shortages. Additionally, the available PPE often did not meet safety requirements in the early

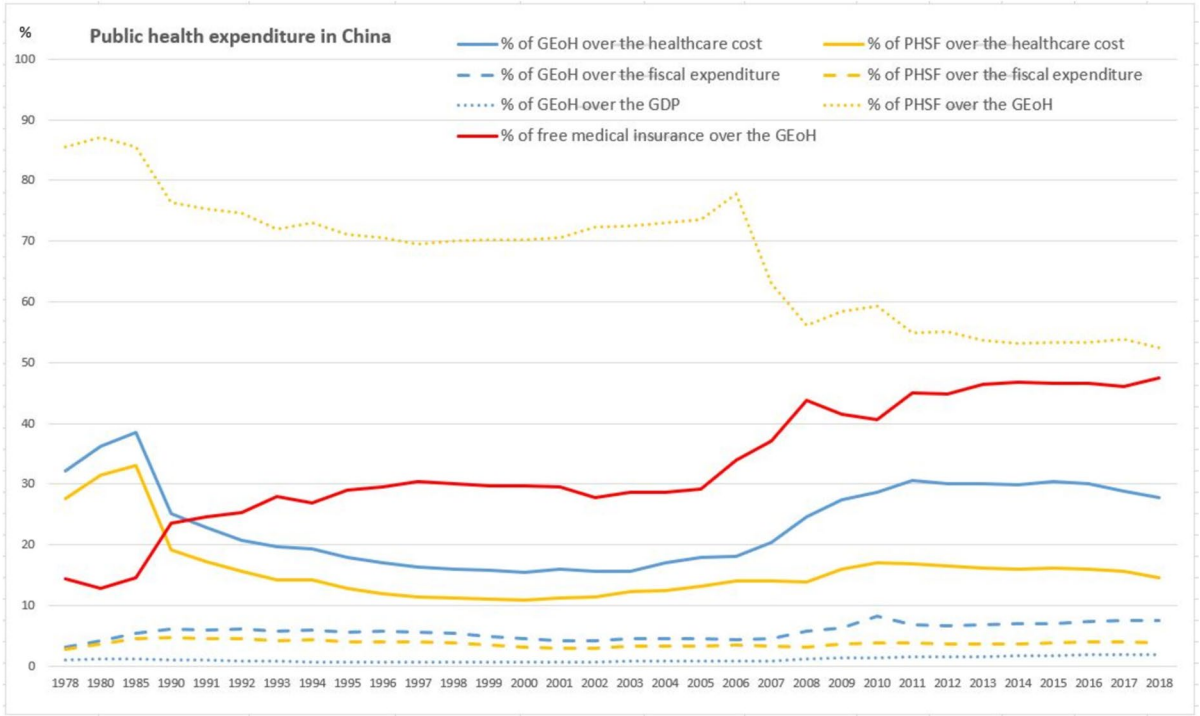

Fig. 1 Changes in public health expenditure during 1978–2018 in China (GEoH: government expenditure on healthcare; PHSF: public health service fund)

epicenters of the pandemic in the US; some doctors and nurses even had to improvise face shields and respirators using everyday products (Lo and De Angelis 2020).

Other strains on healthcare systems have compounded this lack of PPE (Care and Relief 2020). In many countries, the influx of patients has led to insufficient hospital beds and ICU spaces and low staff-to-patient ratios. Doctors may decide who can receive critical care in these conditions and who cannot. These challenges are acute in low/middle-income and high-income countries where critical care and palliative care services are the most significant shortages. Palliative care, which is under-resourced at the best of times, is critical to the elderly population, which are among the most vulnerable groups to COVID-19. The 2017 Lancet Commission on Palliative Care and Pain Relief described the widespread lack of access to inexpensive and effective interventions across the world as a travesty of justice.

Furthermore, today, the worst pandemic in over a century has intensified pre-existing stresses on healthcare systems that provide safe and effective palliative care, including end-of-life care. The lack of healthcare resources, including human resources and clinical equipment, is challenging to supplement quickly. Therefore, after the worst of the pandemic has passed, much more significant investment in healthcare resources, from ensuring adequate stockpiles of PPE to more outstanding training for and promotion of palliative care, should be a priority for governments. Pandemic preparedness should be another focus by increasing the capacity for infectious disease surveillance, contact tracing, and public education.

Risk perception and public understanding

Supporting public understanding of COVID-19 has been critical for enacting and enforcing containment policies. The public perception of risk influences has increased willingness to comply with regulations (e.g., stay-at-home orders, travel restrictions) and population-level morale. Governments must be mindful of these dynamics as they design and implement policies, mainly how to communicate relevant information in a timely and understandable way to the public (the US CDC, for instance, has a training program on public communication during public health emergencies: https://emergency.cdc.gov/cerc/).

We have conducted a nationwide survey in China under a repeated cross-sectional design, to study changes in residents' risk perception of COVID-19 at the early (W1, 21–23 January), middle (W2, 27–28 February), and late stages (W3, 24–27 March) of COVID-19, using a snowball sampling method to recruit 2144, 2021, and 1211 participants, respectively (Table 1). When the health agency responses to the outbreak became more effective in China, residents' perceived susceptibility and severity significantly decreased. Their importance to the epidemic also fell, although remaining high (Fig. 2). Trust in official media platforms (e.g., Xinhua News, China Central Television) gradually increased with time. The official media eventually became the most trusted information source by the Chinese public (Fig. 3). The results from two rounds of surveys—in which residents of Wuhan were represented at 7.6% and 14.8%—suggested that government information helped inform and improve public perception of the disease risks and encouraged compliance with policies.

Global risk perceptions and public understanding varied significantly across geographical regions and cultural contexts. For instance, in Europe, trust in government and health authorities was found to influence the compliance with COVID-19 containment measures, such as in Germany, where public trust was relatively high, saw better compliance compared to countries like Sweden, where trust was lower (Bargain and Aminjonov 2020). Similarly, a study in the United States highlighted that political polarization affected public perception and adherence to health guidelines (Rothgerber et al. 2020). Different political groups exhibited varying levels of trust in the information provided by health authorities. Specifically, compared to progressivism, conservatism showed a contrasting level of compliance with behaviors aimed at preventing the spread of COVID-19. In African countries, the public's risk perception and understanding of COVID-19 were shaped by previous experiences with infectious diseases like Ebola, leading to higher vigilance and quicker adoption of preventive measures in those regions with such experiences compared to those without (Blanco-Penedo et al. 2023).

Table 1 Sociodemographic characteristics of the national survey

Characteristics	Number (%)		
	W1 (n = 2144)	W2 (n = 2021)	W3 (n = 1211)
Age (year)			
≤ 20	126 (5.9)	251 (12.4)	135 (11.1)
> 20–30	970 (45.2)	494 (24.4)	426 (35.2)
> 30–40	720 (33.6)	666 (33.0)	351 (29.0)
> 40–50	257 (12.0)	403 (19.9)	193 (15.9)
> 50–60	64 (3.0)	145 (7.2)	82 (6.8)
> 60	7 (0.3)	62 (3.1)	24 (2.0)
Sex			
Male	804 (37.5)	841 (41.6)	540 (44.6)
Female	1340 (62.5)	1180 (58.4)	671 (55.4)
Educational level			
High school and below	–	207 (10.2)	106 (8.8)
Bachelor	–	1225 (60.7)	622 (51.4)
Graduate and above	–	589 (29.1)	483 (39.8)
Urbanicity			
Urban	–	1795 (88.8)	1103 (91.1)
Rural	–	226 (11.2)	108 (8.9)

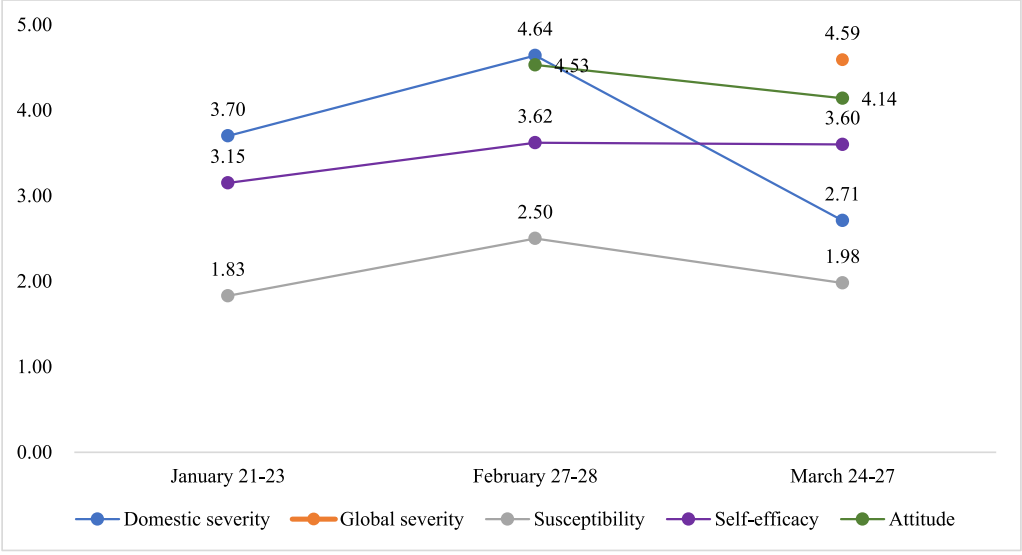

Fig. 2 Changes in the perception of risk of COVID-19 during the early phase of COVID-19 in China (the Y-axis is a unitless scale of 5, with 1 being weakest and 5 being strongest)

Environmental conditions

Recent analysis has shown that 78% of deaths across 66 administrative regions in Italy, Spain, France, and Germany occurred in the five most polluted regions (Ogen 2020). Persistent exposure to air pollution is likely to impair respiratory health, exacerbating the potential effects of COVID-19 infection. Large urban centers, such as the major industrial cities of China, may host large populations of vulnerable individuals owing to the effects of prior air pollution exposure (Qin et al. 2024). Moreover, more heavily polluted

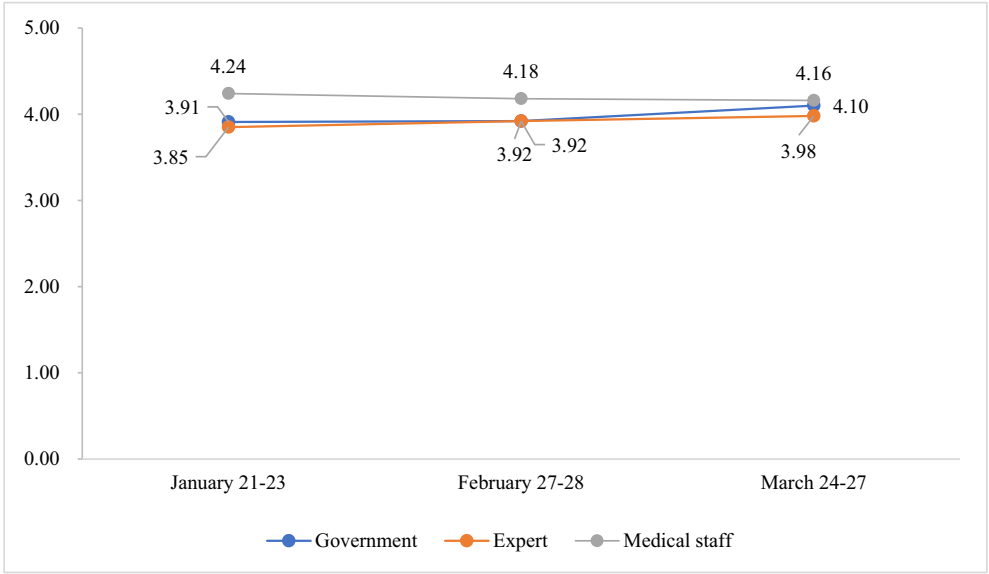

Fig. 3 Changes in Chinese residents' trust in information sources of major media platforms (the Y-axis is a unitless scale of 5, with 1 being weakest and 5 being strongest)

regions usually have higher population density and poorer PPE conditions, resulting in higher incidence rates and case facility rates of COVID-19 in those regions. Indoor air pollution, a severe risk for rural and urban populations in developing countries, such as India, could also exacerbate COVID-19 health impacts. More in-depth ecological and epidemiological research is needed to identify the associations between both outdoor and indoor air pollution and with vulnerability to and incidence rates of COVID-19, as well as spatial patterns of comorbidities related to COVID-19.

In addition to air pollution, other environmental problems could affect COVID-19 spread, such as water and soil pollution that may arise from the increasing use of plastics and drugs. Wastewater could contribute to the transmission of infectious diseases, weakening populations and increasing their vulnerability to severe outcomes from COVID-19 (Kataki et al. 2021). Contaminated water sources can worsen pre-existing health conditions and impede efforts of hygiene practices implemented to curb the spread of COVID-19.

Meteorological conditions also play crucial roles in the transmission dynamics of COVID-19. Significant outbreaks have tended to occur in places that generally experience cool, dry weather. The lipid bilayer envelope surrounding coronaviruses makes them more susceptible to heat, leading to seasonal patterns in case numbers. Most established coronaviruses exhibit winter seasonality, and similar patterns have been observed for SARS-CoV-2 (Dowell and Ho 2004; Liu et al. 2021; Zoran et al. 2021). Research has shown that SARS-CoV-2 can survive for up to 72 h on hard surfaces like plastic and stainless steel at temperatures between 21 and 23 °C and in relative humidity of 40%, although these findings occurred in a laboratory setting, and other factors could influence real-world transmission risks (Hu et al. 2021). Moreover, it was found that COVID-19 increases its transmission during high humidity and low temperatures during winter, while high temperature and low humidity during summer can reduce the transmission of COVID-19 (Coccia 2022; Yin et al. 2022).

Political processes and governance

A necessary perspective in public health emergency and risk management is the worst-case scenario, i.e., the most severe pandemic for which the public health institutions should be prepared. Such strategic planning could prepare for and minimize contingencies that may result in many issues. These issues

include lack of healthcare resources, mental issues due to social distancing measures, unusual weight gain due to eating disorders and lack of physical activity, declines in academic functioning due to school closure, etcetera (Venkatesh and Edirappuli 2020; Yu et al. 2021; Luo et al. 2022a,b; Yang et al. 2022; Zhang et al. 2022a). Also, it is vital to interrupt the emergence of new infectious diseases by refraining from the consumption of wildlife, with legislation being only part of the solution. The ultimate solution lies in changing people's consumption habits. In response to the outbreak of COVID-19, China's government banned all forms of wildlife transaction, accompanied by official and civil society outreach to explain the risks involved in consuming wildlife. Biodiversity conservation, from regulating or banning the wildlife trade to protecting natural habitats, can mitigate the flow of disease pathogens between humans and other animals (Jia et al. 2021a; Li et al. 2020a).

It is also vital to conduct continuing surveillance and interventions to contain COVID-19 eventually (Chen et al. 2020c; Hao et al. 2020; Tian et al. 2020). Although many government responses have thus far been uneven, short-term, and reactive, there has been an overall consensus to prioritize the protection of human life over economic prosperity (Chen et al. 2020b, 2021c). There will likely be a public stock-taking of what constitutes effective action once the pandemic is over. A broader change in political prerogatives, and which has already been evinced by the willingness of so many national governments to undertake lockdown measures on economic activities, is the recognition that the primary role of a government is to serve and protect its people—that matters of health, life and death should be prioritized over GDP. Such a change could be based on the principles of reciprocal rights and responsibilities that form the basis of many political systems worldwide (although they are inconsistently followed). Interconnectedness and interdependence among local communities and countries will become an increasingly undeniable fact for governance. Additionally, the importance of well-resourced and well-prepared healthcare and public health systems will likely rise on political agendas (Chen et al. 2021a, 2020a). If so, a renewed and expanded social contract, with health at the center, could well be a lasting political legacy of COVID-19 (The Lancet 2020).

Conclusions

COVID-19 has had systemic and far-reaching impacts across all sectors of society, affecting regions and populations unevenly. It highlights the need for more comprehensively understanding and documentation of existing processes and mechanisms, including structural determinations of population health and health system, to better guide future decision-making (Sachs et al. 2021). While short-term solutions to COVID-19 are essential, the long-term consequences of COVID-19 necessitate systems thinking and significant reforms to mitigate future risks. Integrating landscape sustainability science with SDGs offers a framework for these necessary reforms, so multiple SDGs related to pandemic prevention could be better coordinated and mutually achieved, such as good health and well-being (SDG 3), quality education (SDG 4), sustainable cities and communities (SDG 11), and partnerships for the goals (SDG 17).

This review has summarized many of the lessons of COVID-19—by pointing to various deficiencies of current systems. However, the full consequences, for example, in mental health, ecology, economy, inequality, or global and local governance, will unfold in the coming years. By revealing both the fragility and the intricate nature of our current systems, COVID-19 has further highlighted the importance, breadth, and comprehensiveness of the 17 SDGs. Sustained cross-country and cross-sector efforts to address these SDGs will lessen the impacts of COVID-19 and reduce the burden of future pandemics. However, this study is a scoping review wherein, for example, we neither adopted a search strategy for systematic reviews nor used experimental or quasi-experimental methods to evaluate causal impacts of COVID-19. Also, this review was conducted by a COVID-19 expert panel formed at the early stage of COVID-19, mainly including opinions from China, North America, and Europe. As COVID-19 has been spreading over nearly all countries and continues to evolve at a rapid pace in some regions and raise new problems in various populations, it will be necessary to revisit, extend, and update these opinions later by a larger, more interdisciplinary panel from more countries.

Author contributions P.J. and S.Y. conceived the idea. M.L., S.D., Y.S. and K.Q. wrote the main manuscript text. All authors critically revised the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

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