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Implications of COVID-19 on global environmental pollution and carbon emissions with strategies for sustainability in the COVID-19 era

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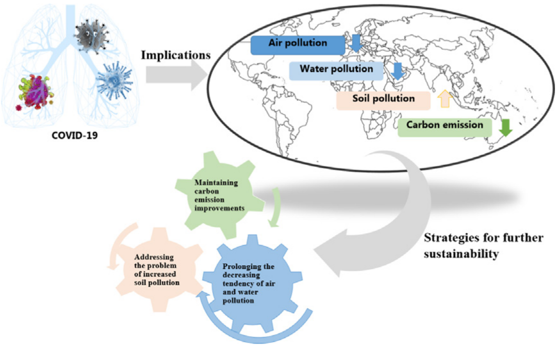
HIGHLIGHTS

- COVID-19 improved $PM_{2.5}$, PM_{10}, NO_2, and CO levels but not SO_2 and O_3 levels.
- COVID-19 improved surface water, coastal water and groundwater except for reservoirs.
- Medical and protective equipment wastes increased during COVID-19 lockdown.
- Carbon emissions reduced due to travel restriction except for essential shipping.
- Sustainable strategies prolong environmental benefits of COVID-19.

GRAPHICAL ABSTRACT



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ABSTRACT

The impacts of COVID-19 on global environmental pollution since its onset in December 2019 require special attention. The rapid spread of COVID-19 globally has led countries to lock down cities, restrict traffic travel and impose strict safety measures, all of which have implications on the environment. This review aims to systematically and comprehensively present and analyze the positive and negative impacts of COVID-19 on global environmental pollution and carbon emissions. It also aims to propose strategies to prolong the beneficial, while minimize the adverse environmental impacts of COVID-19. It systematically and comprehensively reviewed more than 100 peer-reviewed papers and publications related to the impacts of COVID-19 on air, water and soil pollution, carbon emissions as well as the sustainable strategies forward. It revealed that $PM_{2.5}$, PM_{10}, NO_2, and CO levels reduced in most regions globally but SO_2 and O_3 levels increased or did not show significant changes. Surface water, coastal water and groundwater quality improved globally during COVID-19 lockdown except few reservoirs and coastal areas. Soil contamination worsened mainly due to waste from the use of personal protective equipment particularly masks and the packaging, besides household waste. Carbon emissions were reduced primarily due to travel restrictions and less usage of utilities though emissions from certain ships did not change significantly to maintain supply of the essentials. Sustainable strategies post-COVID-19 include the development and adoption of nanomaterial adsorption and microbial remediation technologies, integrated waste management measures, “sterilization wave” technology and energy-efficient technologies. This review provides important insight and novel coverage of the environmental implications of COVID-19 in more than 25 countries across different global regions to permit formulation of specific pollution control and sustainability strategies in the COVID-19 and post-COVID-19 eras for better environmental quality and human health.

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Contents

1. Introduction

The combat against the severe acute respiratory syndrome coronavirus (SARS-CoV-2) has been a top priority for more than 200 countries worldwide since January 2020 (Casado-Aranda et al., 2021). The outbreak has put an unprecedented burden on healthcare, law enforcement agencies, public administration as well as information and communication sector. The cumulative number of confirmed COVID-19 cases worldwide has exceeded 244 million. COVID-19 has caused nearly 5 million deaths so far (Johns Hopkins University Coronavirus Resource Center, 2021). COVID-19 has resulted in many global impacts such as social, economic and environmental impacts. The economic stability of many countries is affected by lockdowns caused by the pandemic, and the restrictions of economic activities in those countries have resulted in the closure of some businesses and the loss of jobs (Casado-Aranda et al., 2021; Cheval et al., 2020; Saadat et al., 2020). In terms of social implications, some severe COVID-19 cases can lead to heart damage, respiratory failure, acute respiratory distress syndrome, and even death (especially in the elderly, who are at high risk of death from the disease) (Rume and Islam, 2020), leading to fear among the global population. The pandemic, which affected people worldwide, has caused major social disruptions, with the cancellation of major international and domestic flights and the breakdown of transportation systems (Mousazadeh et al., 2021; Saadat et al., 2020). Access to basic and essential facilities is also affected by restrictions due to the pandemic (Mousazadeh et al., 2021). Therefore, it is worth analyzing what impacts COVID-19 have on the environment in an in-depth manner. In contrary to the negative socioeconomic impacts, COVID-19 lockdown has also brought some positive environmental improvements to the majority of the countries around the world (Rupani et al., 2020). Rupani et al. (2020) revealed that most countries in the world have witnessed significant decrease of air pollution, and many countries and regions have reported a continuous reduction of greenhouse gases affecting global warming during the pandemic period. Yunus et al. (2020) have similarly elucidated that pollution of the hydrosphere (including lakes, rivers, reservoirs, oceans, and groundwater) has been temporarily mitigated, with pollution levels in the hydrosphere generally lower than during the pre-COVID-19 period. Meanwhile, a substantial decrease in carbon emission was noted during the time of COVID-19 lockdown (Praveena and Aris, 2021; Yunus et al., 2020). It is worth noting that although the novel coronavirus has brought indirect positive effects on the environment, it has also resulted in indirect negative effects. For example, soil-based contamination has become more intense than before because some urban areas have suspended recycling programs and sustainable waste management has been restricted. COVID-19 lockdown has resulted in an increase in organic and inorganic municipal wastes (Zambrano-Monserrate et al., 2020). Furthermore, there is growing concern about global warming or climate change as one of the most urgent crises presently (Nguyen et al., 2021). Although carbon dioxide is not classified as an air pollutant, it is the most important greenhouse gas contributing to global warming. Carbon emissions from human activities have posed threats to the world by increasing global warming and intensifying climate change. Low rainfall, seasonal changes and temperature rise as a result of climate change could lead to low agriculture production (Yoro and Daramola, 2020). Additionally, climate change is also associated with rising sea levels, increased frequency and intensity of storms, as well as a host of socioeconomic and health problems. The activities that produce the most carbon are industries, transportation, energy generation, construction, deforestation, and agriculture (Huisingh et al., 2015). Hofmann et al. (2019) demonstrated that the increase in atmospheric carbon contributes to ocean acidification and that effective removal of CO_2 emissions could well mitigate ocean acidification and its impacts on the marine ecosystems.

The novelty of this literature review is that it is the first systematic discussion of the impacts of COVID-19 on environmental pollution and carbon emissions in different countries in different continents of the world. Other available literature reviews either investigate the global impacts of COVID-19 as a whole, or the variations in one or two types of pollution globally due to COVID-19, and the associated changes in carbon emissions are often examined separately. This review has the novelty of comprehensively reviewing the changes in global environmental pollution and carbon emissions during the COVID-19 pandemic in an integrated manner. Environmental pollution consists of three representative and specific aspects, which are air pollution, water pollution and soil pollution. This literature review investigates the positive and negative implications of COVID-19 on environmental pollution in detail. Secondly, this literature review is innovative in that it not only illustrates the variations of environmental pollution in individual countries and regions of the world during COVID-19, but also suggests a number of sustainable strategies to tackle the worsening of environmental pollution and carbon emission problems after the pandemic. The benefit of this review is not only to provide the populations of the world with the latest information about the global environmental pollution and carbon emissions in the COVID-19 era, but also to help governments and people in different countries and regions to understand the local changes in environmental pollution and carbon emissions during the pandemic. This would enable local authorities and residents to take measures to prolong the benefits of the pandemic and mitigate its negative effects, in relation to the specific circumstances.

The purpose of this article is to review the implications of COVID-19 on environmental pollution and carbon emissions in different countries and regions of the world and to propose measures to solve the environmental pollution and carbon emission problems during and after the pandemic. In this literature review, the following aspects are mainly investigated:

(1) Variations in air pollution in different regions of the world during the COVID-19 pandemic;
(2) Variations in water pollution in different regions of the world during the COVID-19 pandemic;
(3) Variations in soil pollution in different regions of the world during the COVID-19 pandemic;
(4) Variations in carbon emissions in different regions of the world during the COVID-19 pandemic; and
(5) Measures to control environmental pollution as well as reduce carbon emissions after the COVID-19 pandemic. Meanwhile, some practical strategies will be proposed to promote future sustainability.

2. Methodology

2.1. Literature review method

For the purpose of this paper (Fig. 1), peer-reviewed papers related to studies on the effects of COVID-19 on global environmental pollution and carbon emissions were sourced from Google Scholar, ScienceDirect, Scopus, Web of Science, and World Health Organization (WHO) official website. The primary databases used in this paper were Scopus and Web of Science because of the wide range of papers available in these databases. The papers were searched using relevant keywords, including implications of COVID-19, global environmental pollution, air pollution, water pollution, soil pollution, carbon emissions, environmental monitoring system, waste management system, and COVID-19 recovery. The search included only scholarly articles that were in English and had been peer-reviewed prior to publication.

Initial search of the papers revealed over 1000 articles published since the COVID-19 outbreak in December 2019. Since the initial search included all papers on the global environmental impacts of COVID-19, further selection was based on the WHO's delineation of regions to single out papers that focus on the variations in environmental impacts in different continents such as Asia, North, Central and South America, Africa, Europe, and Oceania, Papers that do not differentiate the regions of impacts were removed. Subsequently, studies related to the impacts of COVID-19 on environmental pollution and carbon emissions in specific regions of the world were screened according to the purpose and scope of this paper. The screening yielded more than 100 papers. The Endnote software was also utilized in this process to review the abstracts and general contents of the articles for their relevance. Only studies on the effects of COVID-19 on environmental pollution and carbon emissions in specific countries of the world were extracted and further examined. After careful examination based on the WHO's delineation of regions, 118 papers were selected, which covered the effects of COVID-19 on air pollution, water pollution, soil pollution, and carbon emissions, respectively. Finally, based on the review of the impacts of COVID-19 on global environmental pollution and carbon emissions, sustainability strategies in the era of COVID-19 were proposed.

2.2. Estimation method of daily face mask usage

Data related to population and percentage of urban population (%) were obtained from: Countries in the world by population (Worldometers, 2021). The acceptance rate and daily mask wear per capita are assumed to be 80% and 2, and the weight of masks (tonne) and mask shells (tonne) have been calculated at 4E-6 and 1E-7, respectively (Naughton, 2020; Nzediegwu and Chang, 2020; Tripathi et al., 2020). These data are vital for estimation COVID-19 related daily facemask usage in specific regions.

The estimation of daily face mask usage uses three steps as follows Tripathi et al., 2020: (1) Total used facemasks (tonnes per day) = population x urban population rate x facemask acceptance rate x average daily use of facemasks per capita x 4E-6 tonnes/per facemask; (2) Total plastic packaging (tonnes per day) = population x urban population rate x facemask acceptance rate x average daily use of facemasks per capita x 1E-7 tonnes/per facemask; (3) Total solid waste disposal (tonnes per day) = Total used facemasks + Total plastic packaging.

3. An overview of lockdown restrictions in different regions

In view of the quick transmission of COVID-19, many governments around the world have issued lockdowns to avoid the spread of the coronavirus (Hoang et al., 2021a). The mandatory lockdown imposed by governments to combat this deadly disease is considered the most ambitious isolation measure in the history of humankind. The lockdown has become a benchmark for cities and countries around the world (Le et al., 2020). Lockdown restrictions can significantly reduce the spread of the virus. Atalan (2020) identified through research that effective lockdown at the onset of COVID-19 might have prevented a pandemic. Nonetheless, the lockdown measures have also given rise to a wide range of psychological, environmental, and economic effects.

4. Implications of the pandemic on air pollution

Air pollution is caused by activities such as traffic, industries, refineries, and agricultural activities. COVID-19 caused changes in the levels of air pollution around the world. These changes were due to lockdown and social distancing measures implemented to combat the pandemic, which reduced activities that cause air pollution. This section evaluates the changes in air pollution around the world.

Table 1 summarizes the variations of air pollutants and particulates such as $PM_{2.5}$, PM_{10}, NO_2, CO, O_3 and SO_2 in different cities worldwide. Further discussion of the variations of air pollutants is presented according to the WHO's delineation of regions.

4.1. Asia

In South Korea, air pollutants, namely $PM_{2.5}$, PM_{10}, NO_2, and CO reduced by 16.98 $\mu g/m^3$ (45.45%), 21.61 $\mu g/m^3$ (35.56%), 4.16 ppb (20.41%), and 0.09 ppm (17.33%), respectively in March 2020 compared

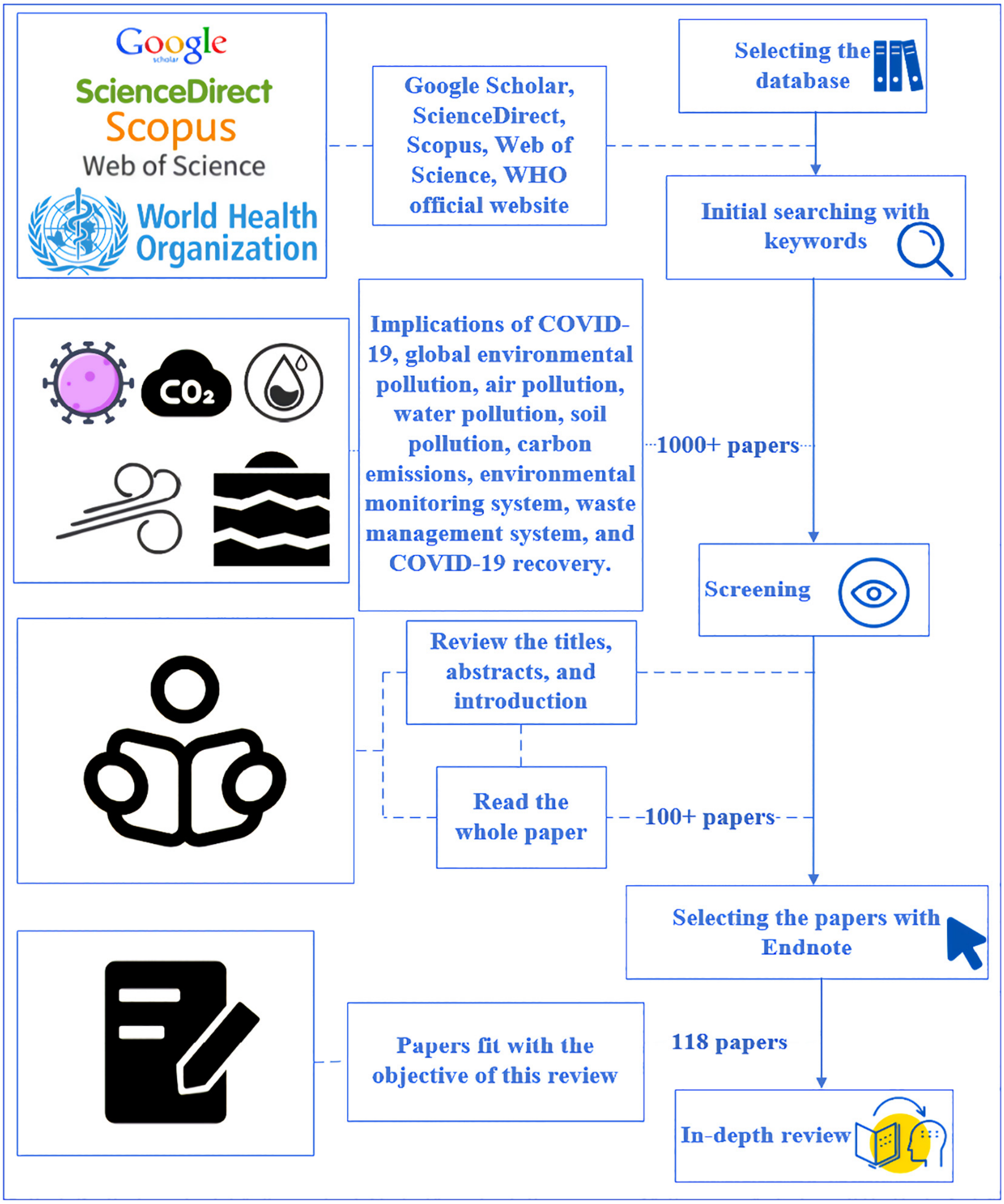


Fig. 1. Flowchart of the five-step literature selection and review for this study.

to March 2019 (Ju et al., 2021). However, the concentrations of O_3 and SO_2 were not observed to change due to the social distancing measures as highlighted in Table 1. Another research conducted in the East Asia region in February 2020 found that the concentrations of NO_2 decreased by 54%, 83%, 33%, and 19% in the Jingjinji, Wuhan, Seoul, and Tokyo areas compared to February 2019 (Ghahremanloo et al., 2021). In India, approximately 40–60% reduction in the particulate matter was observed during the lockdown period (25th March - 3rd May 2020) compared to the period before lockdown (Singh et al., 2020b). Furthermore, an approximate 30–70% and 20–40% reduction in NO_2 and CO were observed, respectively. In Kuala Lumpur, Malaysia, the particulate matter and air pollutants concentrations during the Movement Control Order (MCO) (March 18 until April 21, 2020) were measured and compared with before the MCO (January 1 to March 17, 2020). The study found a reduction of PM_{10}, NO_2, and SO_2 by 0.4%, 54.2%, and 36%, respectively, during the MCO period compared to before the MCO (Othman and Latif, 2021). In Iraq, a study was carried out to compare air pollutants concentrations during six different periods of lockdowns (Hashim et al., 2021). The study found a decrease of $PM_{2.5}$, PM_{10}, and NO_2 by 23.7%, 15.15%, and 7.14%, respectively, during the total lockdown period (March 17 to April 21, 2020) as compared to the partial lockdown period (March 1 to 16, 2020). Although many authors reported a decrease in air pollution due to the pandemic, some authors reported ambiguity in air pollution reduction. Wang et al. (2020) reported a decrease in $PM_{2.5}$ of 9.23, 6.37, 5.35, and 30.79 $\mu g/m^3$ in Beijing, Shanghai, Guangzhou, and Wuhan, respectively. However, these decreases were not enough to avoid severe air pollutions in the regions. Additionally, the authors noted a smaller decrease in $PM_{2.5}$ compared to other pollutants, which was due to unfavorable meteorological conditions. Furthermore, Almond et al. (2021) reported an ambiguity in the reduction of air pollutants during COVID-19 lockdown in China. The authors reported that even in previous years, air pollution was already improving in China. Additionally, COVID-19 lockdown happened around the same time as the Lunar New Year period which was

Table 1
Variations of air pollutants and particulates during and before lockdown worldwide.

Pollutant	Area	Variations	Reference
PM$_{2.5}$	South Korea	March 2019: 37.37 ± 23.95 μg/m^3 March 2020: 20.39 ± 6.31 μg/m^3	(Ju et al., 2021)
	US	March 13 – April 8 2017–2019: 6.29 μg/m^3 March 13 – April 8 2020: 6.00 μg/ m^3	(Berman and Ebisu, 2020)
	Lahore, Pakistan	January 1 – March 22 2020: 176 μg/m^3 March 22 – May 9 2020: 108.9 μg/m^3	(Mehmood et al., 2021)
	Kuala Lumpur, Malaysia	January 1 – March 17, 2020: 18.6 μg/m^3 March 18 – April 21, 2020: 19.3 μg/m^3	(Othman and Latif, 2021)
	Kolkata, India	May 2019: 34.81 μg/m^3 May 2020: 16.86 μg/m^3	(Bera et al., 2020)
	Iraq	March 1–March 16 2020–38 μg/m^3 March 17–April 21 2020–29 μg/m^3	(Hashim et al., 2021)
	South Island, New Zealand	2015–2019: 9.2 g/m^3 March 26 – April 27 2020–7.1 μg/m^3	(Talbot et al., 2021)
	Sydney, Australia	April 2019: 8.52 ± 1.92 ppb April 2020: 7.85 ± 2.92 ppb	(Brimblecombe and Lai, 2021)
	UK	2013–2019: 11.17 μm/m^3 23 March – 30 June 2020: 9.14 μm/m^3	(Higham et al., 2020)
	Lyon, France	Feb 2020: 12.1 μg/m^3 March 17 – May 11, 2020: 18.5 μg/m^3	(Sbai et al., 2021)
	Nice, Italy	2017–2019: 12.7 ± 0.9 μg/m^3 Lockdown 2020: 12.4 ± 1.0 μg/m^3	(Sicard et al., 2020)
PM$_{10}$	South Korea	March 2019: 60.77 ± 31.05 μg/m^3 March 2020: 39.16 ± 7.23 μg/m^3	(Ju et al., 2021)
	Kuala Lumpur, Malaysia	January 1 – March 17, 2020: 24.3 μg/m^3 March 18 – April 21, 2020: 24.2 μg/m^3	(Othman and Latif, 2021)
	Kolkata, India	May 2019: 88.99 μg/m^3 May 2020: 35.66 μg/m^3	(Bera et al., 2020)
	Iraq	March 1 – March 16 2020: 132 μg/m^3 March 17 – April 21 2020: 112 μg/m^3	(Hashim et al., 2021)
	South Island, New Zealand	2015–2019: 13.8 μg/m^3 March 26 – April 27 2020: 9 μg/m^3	(Talbot et al., 2021)
	Lyon, France	Feb 2020: 20.0 μg/m^3 March 17 – May 11, 2020: 24.5 μg/m^3	(Sbai et al., 2021)
	Nice, Italy	2017–2019: 25.7 ± 3.9 μg/m^3 Lockdown 2020: 24.1 ± 3.4 μg/m^3	(Sicard et al., 2020)
NO$_2$	South Korea	March 2019: 20.38 ± 6.63 ppb March 2020: 16.22 ± 4.95 ppb	(Ju et al., 2021)
	US	March 13 – April 8 2017–2019: 18.68 ppb March 13 – April 8 2020: 13.92 ppb	(Berman and Ebisu, 2020)
	Beijing-Tianjin-Hebei, China	February 2019: 9.3E+15 molecules/cm^2 February 2020: 4.3E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Wuhan, China	February 2019: 1.5E+16 molecules/cm^2 February 2020: 2.5E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Tokyo, Japan	February 2019: 9.8E+15 molecules/cm^2 February 2020: 7.9E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Kuala Lumpur, Malaysia	January 1 – March 17, 2020: 12.1 ppb March 18 – April 21, 2020: 5.54 ppb	(Othman and Latif, 2021)
	Barcelona, Spain	(16/03–24/05/)2015–2019: 33.3 μg/m^3 (16/03–24/05/)2020: 15.3 μg/m^3	(Querol et al., 2021)
	Kolkata, India	May 2019: 16.48 μg/m^3 May 2020: 10.66 μg/m^3	(Bera et al., 2020)
	Iraq	March 1 – March 16 2020: 42 μg/m^3 March 17–April 21 2020: 39 μg/m^3	(Hashim et al., 2021)
	South Island, New Zealand	2015–2019: 19.7 μg/m^3 March 26–April 27 2020: 9.8 μg/m^3	(Talbot et al., 2021)
	Sao Paulo, Brazil	May 2015–2019: 9.1E+15 molecules/cm^2 May 2020: 5.28E+15 molecules/cm^2	(Brandao and Foroutan, 2021)
	Sydney, Australia	April 2019: 8.91 ± 4.94 μg/m^3 April 2020: 7.95 ± 2.64 μg/m^3	(Brimblecombe and Lai, 2021)
	UK	2013–2019: 22.92 μm/m^3 23 March – 30 June 2020: 13.21 μm/m^3	(Higham et al., 2020)
	Lyon, France	Feb 2020: 36.8 μg/m^3 March 17–May 11, 2020: 12.0 μg/m^3	(Sbai et al., 2021)
	Nice, Italy	2017–2019: 34.0 ± 7.3 μg/m^3 Lockdown 2020: 12.5 ± 2.4 μg/m^3	(Sicard et al., 2020)
	Milan, Italy	February 7–20, 2020: 53.4 μg/m^3 March 23–April 5, 2020: 22.1 μg/m^3	(Collivignarelli et al., 2020)
CO	South Korea	March 2019: 0.513 ± 0.134 ppm March 2020: 0.387 ± 0.040 ppm	(Ju et al., 2021)
	Beijing-Tianjin-Hebei, China	February 2019: 3.23E+18 molecules/cm^2 February 2020: 2.98E+18 molecules/cm^2	(Ghahremanloo et al., 2021)
	Wuhan, China	February 2019: 3.51E+18 molecules/cm^2 February 2020: 3.38E+18 molecules/cm^2	(Ghahremanloo et al., 2021)

(continued on next page)

Table 1 (*continued*)

Pollutant	Area	Variations	Reference
	Tokyo, Japan	February 2019: 2.51E+18 molecules/cm^2 February 2020: 2.48E+18 molecules/cm^2	(Ghahremanloo et al., 2021)
	Kuala Lumpur, Malaysia	January 1 – March 17, 2020: 0.88 ppm March 18 – April 21, 2020: 0.87 ppm	(Othman and Latif, 2021)
	Barcelona, Spain	(16/03–24/05/)2015–2019: 322.8 μg/m^3 (16/03–24/05/)2020: 256.9 μg/m^3	(Querol et al., 2021)
	Peru	March 6, 2020: 2.5 ppm May 4, 2020: 0.5 ppm	(Roman-Gonzalez et al., 2020)
	Kolkata, India	May 2019: 0.52 mg/m^3 May 2020: 0.36 mg/m^3	(Bera et al., 2020)
	Edmonton, Canada	March 2018: 0.14 ppm March 2020: 0.07 ppm	(Tian et al., 2021)
O_3	South Korea	No change	(Ju et al., 2021)
	Kuala Lumpur, Malaysia	January 1 – March 17, 2020: 18.1 ppb March 18 – April 21, 2020: 19.9 ppb	(Othman and Latif, 2021)
	Barcelona, Spain	(16/03–24/05/)2015–2019: 85.3 μg/m^3 (16/03–24/05/)2020: 86.5 μg/m^3	(Querol et al., 2021)
	Peru	March 5, 2020: 0.1175 mol/m^2 May 3, 2020: 0.111 mol/ m^2	(Roman-Gonzalez et al., 2020)
	Kolkata, India	May 2019: 31.92 μg/m^3 May 2020: 38.68 μg/m^3	(Bera et al., 2020)
	Iraq	March 1 – March 16 2020: 40 μg/m^3 March 17 – April 21 2020: 44 μg/m^3	(Hashim et al., 2021)
	UK	2013–2019: 59.38 μm/m^3 23 March – 30 June 2020: 66.03 μm/m^3	(Higham et al., 2020)
	Lyon, France	Feb 2020: 33.5 μg/m^3 March 17 – May 11, 2020: 68.9 μg/m^3	(Sbai et al., 2021)
	Nice, Italy	2017–2019: 62.6 ± 2.1 μg/m^3 Lockdown 2020: 77.6 ± 1.3 μg/m^3	(Sicard et al., 2020)
SO_2	South Korea	No change	(Ju et al., 2021)
	Beijing-Tianjin-Hebei, China	February 2019: 1.3E+16 molecules/cm^2 February 2020: 1.3E+16 molecules/cm^2	(Ghahremanloo et al., 2021)
	Wuhan, China	February 2019: 3.9E+15 molecules/cm^2 February 2020: 1.1E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Tokyo, Japan	February 2019: 2.7E+15 molecules/cm^2 February 2020: 9.4E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Kuala Lumpur, Malaysia	January 1 – March 17, 2020: 0.89 ppb March 18 – April 21, 2020: 0.57 ppb	(Othman and Latif, 2021)
	Barcelona, Spain	(16/03–24/05/)2015–2019: 2.5 μg/m^3 (16/03–24/05/)2020: 1.9 μg/m^3	(Querol et al., 2021)
	Peru	March 5, 2020: 0.0002 mol/m^2 May 2, 2020: 0.00035 mol/m^2	(Roman-Gonzalez et al., 2020)
	Kolkata, India	May 2019: 6.82 μg/m^3 May 2020: 2.54 μg/m^3	(Bera et al., 2020)
	UK	2013–2019: 2.26 μm/m^3 23 March – 30 June 2020: 3.95 μm/m^3	(Higham et al., 2020)
HCHO	Beijing-Tianjin-Hebei, China	February 2019: 7.4E+15 molecules/cm^2 February 2020: 6.5E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Wuhan, China	February 2019: 7.3E+15 molecules/cm^2 February 2020: 6.5E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Tokyo, Japan	February 2019: 3.9E+15 molecules/cm^2 February 2020: 3.5E+15 molecules/cm^2	(Ghahremanloo et al., 2021)
	Peru	March 5, 2020: 0.002 mol/m^2 May 8, 2020: 0.0006 mol/m^2	(Roman-Gonzalez et al., 2020)

observed to have lower air pollutants than other periods of the year in previous years. Lastly, the authors argued that, although there was a significant drop in NO_2 due to a decrease in the use of transportation, there was an increase in O_3 and the decrease in SO_2 was very slight, hence the overall changes in air pollution did not yield significant health benefits.

4.2. North and South America

In California, US, respective drops of 38%, 49%, and 31% in NO_2, CO and $PM_{2.5}$ were observed during the lockdown period (March 19–May 7, 2020) compared to the pre-lockdown period (January 26–March 18, 2020) (Liu et al., 2021c). In Peru, air pollution data were sourced from satellites during quarantine in 2020. The study revealed that the concentrations of CO, O_3, and HCHO decreased by 80%, 5.53%, and 70% respectively in May during quarantine as compared to March before quarantine, as shown in Table 1 (Roman-Gonzalez et al., 2020). In Sao Paulo, Brazil, a decrease of 42% of NO_2 was observed in May 2020 during lockdown as compared to May (2015–2019) pre-COVID-19 period (Brandao and Foroutan, 2021). Additionally, the $PM_{2.5}$ particulates were studied but there were no significant changes observed during and before COVID-19, which was probably attributed to the wildfires that generated particulates over the study period. In Edmonton, Canada, a decrease of NO_2 and CO by 78.6% and 50% was observed during the lockdown period in 2020 compared to the year 2018 (Tian et al., 2021). There was no significant change in the SO_2 concentrations.

4.3. Africa

In Cairo, Egypt, there was a decrease in NO_2 and CO by 15% and 5% respectively during the lockdown in 2020 compared to the baseline period of 2015–2019 (Mostafa et al., 2021). In Casablanca, Morocco, a decrease in NO_2, $PM_{2.5}$, and CO concentrations by 12 μg/m^3, 18 μg/m^3 and 0.04 mg/m^3 was observed respectively during the lockdown in 2020 as compared to years 2016–2019 for the same period (Khomsi et al., 2021).

In Port Harcourt, Nigeria, a study on the air quality index revealed a respective decrease of CO, $PM_{2.5}$ and PM_{10} from a range of 8–28 ppm, 20–140 μg/m^3 and 15–135 μg/m^3 before lockdown to a range of 4–16 ppm, 10–110 μg/m^3 and 10–90 μg/m^3 during lockdown (Adeyemi et al., 2021).

4.4. Europe

A study was done in Spain by collecting information from different cities' air pollution monitoring stations during lockdown (March–May) and comparing the results with information collected in previous years (2015–2019), as shown in Table 1. The comparison of Barcelona city showed that $PM_{2.5}$, PM_{10}, NO_2, CO and SO_2 reduced by 19%, 32%, 54%, 20%, and 25% during lockdown compared to previous years (Querol et al., 2021). Another analysis was done in Moscow by comparing the air pollutants concentrations in 2020 during the lockdown, with those of previous years (Ginzburg et al., 2020). The analysis revealed that CO and NO_2 decreased by 38% and 55% in residential areas in April 2020 compared to April in 2017–2019. In the UK, data from air quality sensors and meteorological stations were analyzed during lockdown from 23 March to 30 June 2020 and compared with the average of 7 years from 2013 to 2019. The results showed that concentrations of $PM_{2.5}$ and NO_2 decreased by 18.2% and 42.36%, while those of SO_2 and O_3 increased by 42.78% and 10.07%, respectively (Higham et al., 2020). In Lyon, France, the lockdown period from March 17 to May 11, 2020 caused a decrease in $NO_{2,}$ NO, and CO values by 67%, 78%, and 62%, while an increase in $O_{3,}$ $PM_{10,}$ and $PM_{2.5}$ values by 105%, 23%, and 53% was observed (Sbai et al., 2021).

4.5. Oceania

In the South Island of New Zealand, the concentrations of $PM_{2.5}$, PM_{10}, and NO_2 reduced by 22.6%, 34.1%, and 50%, respectively, during level 4 lockdown from March 26–April 27, 2020, compared to the years 2015–2019 before the pandemic (Talbot et al., 2021). In Sydney, Australia, the concentrations of NO_2 and $PM_{2.5}$ decreased by 7.9% and 10.8% in April 2020 during restrictions compared to April 2019 before the pandemic. The changes, however, were less compared to other countries (Brimblecombe and Lai, 2021).

It is clear that most of the pollutants and particulate matters such as $PM_{2.5}$, PM_{10}, NO_2, and CO decreased in most cities around the world during the COVID-19 lockdown phases, as shown in Fig. 2. In contrast, the ozone concentration increased in different cities due to the decrease in nitrogen dioxide that depletes the ozone in the atmosphere. Additionally, SO_2 also increased in different cities because it was produced by fossil fuel combustion in industries and powerplants which continued operations even during the lockdown period. The air pollution and particulates data in the studies reviewed were collected mainly from national air quality monitoring stations and satellites, which were reported to be reliable (Table 2). The data obtained were then analyzed by statistical software.

5. Implications of COVID-19 on water pollution

With COVID-19 spreading globally, the risk of infection from the new coronavirus is forcing governments around the world to take measures to quarantine and maintain social distance. The cessation of recreational commercial activities at beaches and harbors has reduced the risk of coastal water contamination with harmful substances such as plastics. This has led to a temporary improvement in coastal environmental conditions, with beaches in conditions closer to marine protected areas (Ormaza-Gonzaìlez et al., 2021). Meanwhile, same as coastal water, surface water quality has also improved in a short period of time due to nationwide lockdowns implemented. Surface water improved because continuous domestic sewage, industrial effluent and agricultural wastewater discharges into surface water catchments during lockdown significantly decreased, which reduced the risk of heavy metal pollution as well as other pollution in the surface water (Chakraborty et al., 2021; Tokatlı and Varol, 2021). Groundwater contamination also appeared to be getting better during the COVID-19 lockdown (Karunanidhi et al., 2021a). However, the problem of water contamination also exacerbated in some places during the pandemic and is foreseen to rebound after the pandemic has been effectively controlled.

5.1. Variations of surface water quality

The quality of surface water has been affected by urban development, industrial production, deforestation and inappropriate use of chemicals and increased human activities (Jani et al., 2021; Karunanidhi et al., 2021b; Xu et al., 2021). The reduction of human activities because of lockdown has contributed, to some degree, to the improvement and restoration of the aquatic environment. Biodiversity and aquatic ecosystems that have been under anthropogenic pressure for a long time have had a chance to recover. Therefore, it becomes important to assess

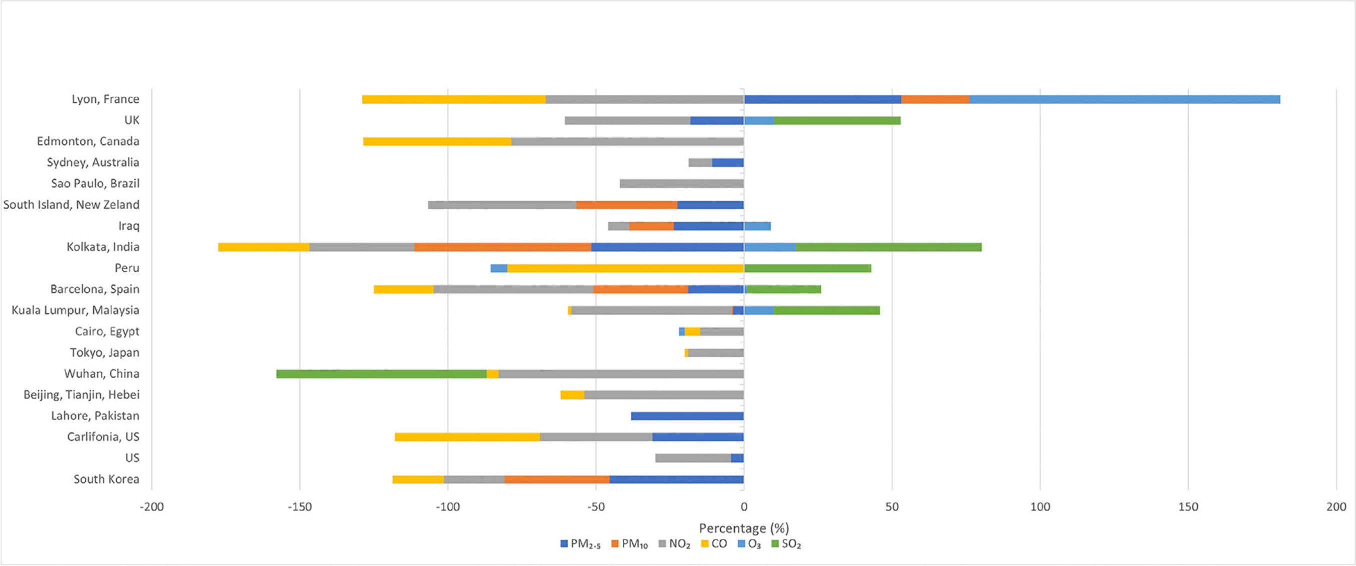


Fig. 2. Percent changes of air pollutants and particulates in different cities/countries during lockdown.

Table 2
Air pollution and particulates measurement methods.

S/no	Region	Methods	References
1	Asia-South Korea	Atmospheric monitoring stations	(Ju et al., 2021)
2	Asia-Pakistan	TROPOspheric monitoring instrument/SAS software	(Mehmood et al., 2021)
3	Asia-Malaysia	Continuous air quality monitoring station/Thermo Scientific Models 43i, 42i, 48i and 49i	(Othman and Latif, 2021)
4	Asia-India	State Pollution Control Board/LANDSAT-8 OLI and LANDSAT-7 ETM	(Bera et al., 2020)
5	Asia-China, South Korea and Japan	Satellite remote sensing	(Ghahremanloo et al., 2021)
6	North America-US	OpenAQ API	(Berman and Ebisu, 2020)
7	South America-Brazil	Ozone monitoring instrument/air quality information systems	(Brandao and Foroutan, 2021)
8	South America-Peru	Sentinel-5 Precursor/VISAN tool	(Roman-Gonzalez et al., 2020)
9	North America-Canada	Monitoring station/Sentinel-5P satellite/MATLAB	(Tian et al., 2021)
10	Europe-UK	Air-quality sensors/Met Office stations	(Higham et al., 2020)
11	Europe-France	Monitoring stations	(Sbai et al., 2021)
12	Europe-Spain	Air quality monitoring (AQM) stations	(Querol et al., 2021)
13	Europe-Italy	Meteorological control units/air quality control units	(Collivignarelli et al., 2020)
14	Africa-Morocco	Air quality stations	(Khomsi et al., 2021)
15	Africa-Nigeria	Integrated modeling of atmospheric composition/EGVOC-180	(Adeyemi et al., 2021)
16	Africa-Egypt	Satellite monitoring	(Mostafa et al., 2021)
17	Oceania-New Zealand	Stations/random forest algorithms	(Talbot et al., 2021)
18	Oceania-Australia	Monitoring stations/Vassarstat	(Brimblecombe and Lai, 2021)

the implications of the COVID-19 pandemic on water pollution (Jani et al., 2021). Our literature review found that during the lockdown, biological oxygen demand (BOD), coliform counts, and other pollutant concentrations decreased and dissolved oxygen levels increased in most lakes and rivers around the world. On the contrary, the water quality of reservoirs in some regions has become more contaminated due to the increase of chlorophyll-a and phycocyanin as a result of lockdown (Alcantara et al., 2021). Table 3 summarizes the variations of surface water pollution in selected countries and regions in each continent of the world.

From the summary in Table 3, it can be seen that the Heavy Metals Pollution Index, Heavy Metals Evaluation Index, and Weighted Water Quality Index of surface water in the Limpopo region of Africa showed a significant improvement after the COVID-19 outbreak. Similar to the African region, the surface water pollution problems in various regions and countries in Asia have also temporarily improved. In India and Turkey, the concentrations of heavy metal pollutants in surface water showed a significant reduction, with the Heavy Metals Pollution Index (HPI) in India being less than 15. The water quality parameters and fluorescent fraction intensities (WT-C1(20) and WT-C2(20)) of the Jiangsu section of the Beijing-Hangzhou Grand Canal in China also dropped to a lower level. The dissolved oxygen (DO) level of surface water in Nepal increased by 1.5 times, while the biological oxygen demand (BOD) and chemical oxygen demand (COD) decreased by 1.5 times and 1.9 times, respectively. Among the European regions, the Venice channel in Italy has improved water clarity due to a significant reduction of tourists as a result of the pandemic lockdown. Meanwhile, the dissolved oxygen (DO) level of the lakes in the Minnesota region of the United States also showed a similar upward trend. The decrease in HPI values for Peru confirmed the improvement of surface water quality during the epidemic lockdown. It is worth noting that the reservoirs in the São Paulo region of Brazil in South America showed a different situation from other regions in terms of surface water variations, as the reservoirs in this region were closed due to the pandemic, leading to problems in

Table 3
Implications of COVID-19 on surface water pollution.

Continents	Area	Impacts	Variations/key findings	Reference
Africa	Limpopo, Africa	◆	• The temporal (2016–2019) trend of water quality shows a deteriorating trend. • The Heavy Metals Pollution Index (HPI), Heavy Metals Evaluation Index (HEI) and Weighted Water Quality Index (WQI) have improved.	(Molekoa et al., 2021)
Asia	Lucknow city, India	◆	• The concentrations of all six heavy metals (As, Cd, Cr, Fe, Mn, Pb) in the Gomti River decreased significantly. • The Heavy Metals Pollution Index (HPI) decreased at all sites and some of the observed areas were able to achieve a low pollution situation (HPI <15).	(Khan et al., 2021)
	Jiangsu, China	◆	• Water quality parameters and fluorescent fraction intensities (WT-C1(20)) of the Beijing-Hangzhou Grand Canal decreased significantly. • Gradual increase was observed after domestic outbreak was under control.	(Shen et al., 2021)
	Turkey	◆	• The concentrations of Cr, Ni, Zn, Cu, As, Pb, and Cd in the surface waters of the Merrick-Elgin River basin decreased significantly. • Significant improvements in HPI and HEI were observed at all monitoring stations.	(Tokatlı and Varol, 2021)
	Nepal	◆	• Dissolved oxygen (DO) levels improved by a factor of 1.5. • Biological oxygen demand (BOD) and chemical oxygen demand (COD) decreased 1.5 times and 1.9 times, respectively.	(Pant et al., 2021)
Europe	Venice, Italy	◆	• Due to the worldwide pandemic and the decrease in the number of tourists, the channels in Venice are now cleaner than before	(Bhat et al., 2021)
South and North America	São Paulo, Brazil	◇	• Chlorophyll a (chl-a) and phycocyanin (PC) concentrations increased substantially in Guarapiranga and Billings reservoirs. • It is worth noting that phycocyanin (PC) increased by almost 500%.	(Alcantara et al., 2021)
	Peru	◆	• The PERMANOVA partition shows a strong and pronounced spatial effect of water quality variability. • HPI shows that only 13.33% of the sampling area exceeds the critical pollution value (150). • 86.67% of the sampling areas had low levels of cadmium pollution (<1).	(Custodio et al., 2021)
	Minnesota, USA	◆	• Dissolved oxygen (DO) levels at sampling sites along the St. Louis River have increased, which is a good indicator of improved river water quality. • There was also a trend of decreasing sediment in the river.	(Hamidi et al., 2021)

Note: ◆ indicates that COVID-19 has a positive impact on the pollution of surface water. ◇ indicates that COVID-19 has a negative effect on the contamination of surface water.

reservoirs management and maintenance. This resulted in an increase in chlorophyll-a and phycocyanin, thereby exacerbating the problem of water contamination in the reservoirs.

5.2. Variations of coastal water quality

Clean coastal water is essential for marine life and the health of beach visitors. Coastal water contamination is a serious environmental health risk affecting most of the coastal environments of the world. Hence, monitoring and improving coastal water quality has become a necessity (Cherif et al., 2020). A study on coastal marine litter pollution by Okuku et al. (2021) demonstrated that most of the coastal litter originated from soil and that the source of pollution was mainly made up of plastics. Coastal ecosystems around the world account for about 10% of the total ocean area. Nowadays, the coastal waters of many countries are affected by large amounts of anthropogenic pollutants that severely affect marine aquatic ecology and sometimes lead to eutrophication of the oceans. In recent years, environmental parameters such as chlorophyll *a* (chl-a) which is a proxy for phytoplankton biomass and diffuse light attenuation coefficient K_d (490) which is an index of water clarity or turbidity can be effectively measured with satellite inversions to monitor the water quality of coastal waters (Lotliker et al., 2021; Vijay et al., 2021). Owing to the impacts of COVID-19, tourism and commercial activities on the beach have to be temporarily restricted. Meanwhile, factories near the coast were temporarily closed, which have led to an improvement in the quality of coastal water. Nevertheless, not all countries and regions have recorded improved coastal waters. The production of masks and other products made of polymeric materials (gloves, protective clothing) has increased significantly during the lockdown period, and if these protective products are not properly disposed of, it is likely that they would enter the marine environment and further contaminate the coastal waters. Table 4 summarizes the variations of coastal water pollution in selected countries and regions in each continent of the world.

Table 4 indicates that coastal water quality improved in most countries and regions during COVID-19. Coastal water pollution problems in Morocco and Kenya in Africa have improved significantly during the pandemic, with a significant reduction in *E. coli* concentrations on the west coast of Morocco and a rapid decrease in litter floating on the Kenyan coastal waters. Similarly, coastal water contamination in Asian countries was also mitigated to some extent during the pandemic lockdown. More than 50% of reduction in chl-a concentration demonstrates that coastal waters in the Pakistan region did improve significantly during COVID-19. Compared to the chl-a concentration of 10 mg/m^3 before lockdown, the chl-a decreased to less than 5 mg/m^3 after lockdown. An overall decline in chl-a concentrations in coastal waters was also found in India of the Asian region. Moreover, the concentration of suspended particulate matter (SPM) decreased by 15.48% and 37.50% in Chennai and Enore harbors, respectively. The diffuse attenuation coefficient K_d (490) was significantly and positively correlated with SPM, therefore, the reduction K_d (490) implies a reduction in SPM, and consequently the improvement of coastal water quality. It is noteworthy that very few articles discuss the impacts of COVID-19 on water pollution problems in Europe, and this literature review only found coastal water pollution variations in Cyprus. Concentrations of micro, medium and large plastic contamination on the water along the Cyprus coast decreased significantly during the pandemic lockdown. Ecuador in the South America and Belize in the Central America have shown a significant decrease in coastal water chl-a concentrations and K_d (490), as in other continents. Nevertheless, it is worth noting that the increase in the production of personal protective equipment (PPE) such as masks and gloves in Argentina has also caused a more serious problem of plastic disposal, which eventually led to a further contamination of coastal waters.

5.3. Variations of groundwater quality

Groundwater is an essential global resource for irrigation as well as domestic and industrial activities, particularly in arid and semi-arid regions (Karunanidhi et al., 2021a). Groundwater quality is an important environmental issue on a global scale. The rapid industrialization and urbanization during the last few decades have caused various contaminants to seriously affect the groundwater environment. Among the different pollutants, heavy metals are considered to be the most significant and harmful pollutants for groundwater. Numerous groundwater heavy metal contamination studies have revealed that anthropogenic factors

Table 4
Implications of COVID-19 on coastal water pollution.

Continents	Area	Impacts	Variations/key findings	Reference
Africa	Morocco	◆	• The problem of serious bacterial contamination of Boukhalef water has been mitigated to some extent. • The level of *Escherichia Coli* (*E. coli*) on the west coast of Tangier was significantly reduced. *E. coli* colony forming unit (CFU) values were almost below 200 *E. coli* CFU/100 mL.	(Cherif et al., 2020)
	Kenya	◆	• The amount of marine litter on beaches has been significantly reduced. • Targeted interventions on beaches can significantly reduce marine litter pollution and thus improve the quality of coastal waters.	(Okuku et al., 2021)
Asia	Pakistan	◆	• Chl-a decreased from an average concentration of more than 10 mg/m^3 to less than 5 mg/m^3 in coastal areas of Pakistan, indicating a 50% decrease in Chl-a concentration in coastal areas.	(Shafeeque et al., 2021)
	India	◆	• The concentration of suspended matter (SPM) decreased by 15.48% and 37.50% in Chennai and Enore harbors, respectively. • The diffuse attenuation coefficient K_d (490) showed a significant positive correlation with SPM. The reduction in SPM indicates the improvement in coastal water quality. • The overall reduction in Chl-a in coastal waters indicates a net reduction in nutrient loading.	(Mishra et al., 2020; Vijay et al., 2021)
Europe	Cyprus	◆	• Clean Coast Index (CCI), Waste Accumulation Rate (WAR) and Waste Accumulation Index (WAI) improved as a result of significant decreases in micro-, medium and large plastic concentrations on coastal waters.	(Loizia et al., 2021)
South and Central America	Ecuador	◆	• Decreases in chlorophyll and attenuation coefficients K_d (490) indicate that the quality of the coastal environment has improved. • More fish and large marine organisms were observed near the coast, which supports the improvement in the water quality of seawater.	(Ormaza-Gonzaìlez et al., 2021)
	Belize	◆	• The attenuation coefficient K_d (490) was used as an indicator of water quality, and a lower K_d (490) indicated increased water clarity. • Heavy traffic areas (HTAs) showed a decreasing trend in K_d (490).	(Callejas et al., 2021)
	Argentina	◇	• The misuse and mismanagement of personal protective equipment (PPE) and the significant increase in the production of masks and other products made of polymeric materials (gloves, protective clothing) have further contributed to plastic pollution in coastal waters. • Anti-viral polymeric textile waste may also have long-term negative effects on the aquatic environment.	(Ardusso et al., 2021)

Note: ◆ indicates that COVID-19 has a positive impact on the pollution of coastal water. ◇ indicates that COVID-19 has a negative effect on the contamination of coastal water.

such as municipal waste leachate, manufacturing, fertilizer application, and household waste are important causes of groundwater contamination (Aravinthasamy et al., 2021). Nevertheless, the near-term data on the variations of groundwater quality on a global scale during COVID-19 were lacking. Therefore, it is difficult to develop a comprehensive table with a global perspective for groundwater. Despite this, through literature search, it is possible to deduce global variations in groundwater quality from the publications in individual countries and regions during the pandemic. For example, the COVID-19 lockdown was identified as having positive impacts on groundwater quality based on shallow groundwater samples tested in Coimbatore, South India, where groundwater samples indicated a reduction in heavy metal concentrations and biological parameters (Aravinthasamy et al., 2021). Analyses of heavy metals (Fe, Mn, Ni, Cr, Pb) and biological parameters (*E. coli*, fecal coliforms, fecal streptococci and total coliforms) found that the concentrations of Mn, Ni, Cr and Pb were substantially reduced (Mn from 2 mg/L to 0 mg/L; Ni from 13 mg/L to 10 mg/L; Cr from 7 mg/L to 5 mg/L, Pb from 13 mg/L to 8 mg/L). Similarly, the mean counts of Fecal coliform, Total coliform and *E. coli* had declined from 74.29 to 45.31 MPN/mL, from 66.77 to 45.21 MPN/mL, and from 27.93 to 19.53 MPN/mL, respectively as a result of COVID-19 lockdown (Aravinthasamy et al., 2021). The research findings on groundwater contamination during the outbreak suggest that the pandemic lockdown did have a positive effect on the alleviation of groundwater contamination.

5.4. Summary for variations of water quality

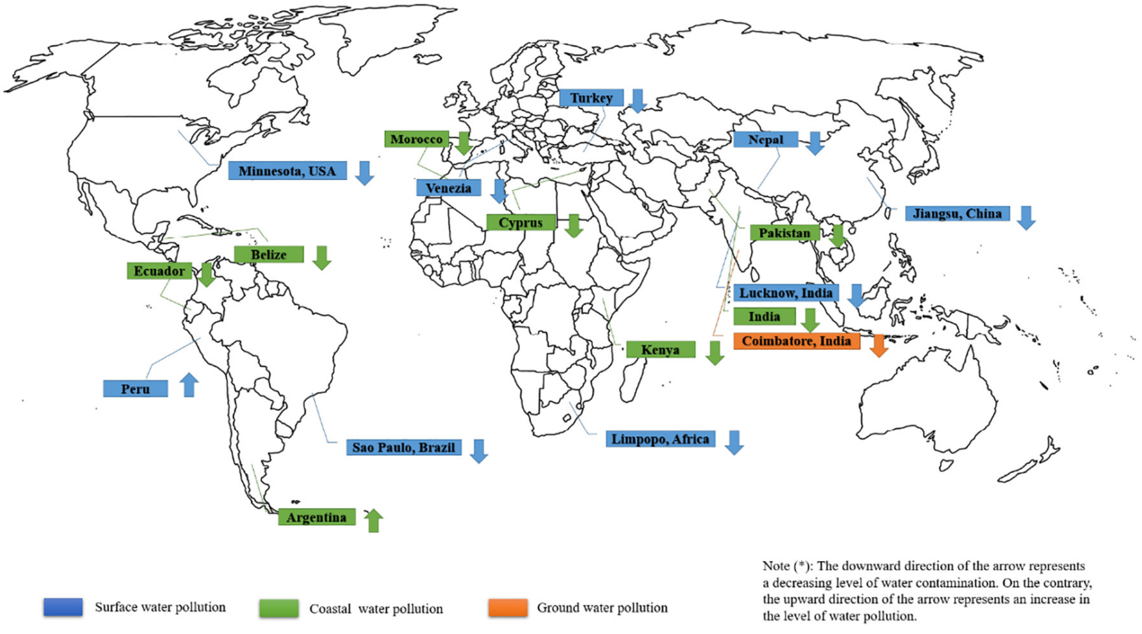
Overall, the different categories of water bodies around the world (including surface water, coastal water and groundwater) have significantly improved during the COVID-19 lockdown, with the exception of a few reservoirs and coastal water areas where the lockdown has resulted in mismanagement and improper disposal of PPE waste, which has led to further water pollution. The Table 3 and Table 4 also illustrate that water pollution problems in most regions of the world have been mitigated by the pandemic lockdown. The variations of water quality in different types of water bodies during the pandemic are presented in Fig. 3.

Based on Fig. 3, it is clear that COVID-19 lockdown of the cities has played a very positive role in improving the pollution of water bodies on a global scale.

6. Implications of COVID-19 on soil pollution

The leading cause of COVID-19 on soil pollution is the increasing accumulation of solid waste. Since the outbreak of the novel coronavirus in December 2019, governments around the world have taken a number of measures to prevent and control the spread of the virus. Because COVID-19 is highly infectious, it can spread rapidly through air and respiratory droplets (Heller et al., 2020; Ren et al., 2020). As a result, governments around the world have begun to advise people to wear masks properly to reduce person-to-person contact, which can effectively reduce the spread of the virus through air or respiratory droplets (WHO, 2020). Since the outbreak of the virus, the demand for masks has been increasing. Masks have become necessary for people going to work, shopping, schools, and other outdoor activities. Used masks, plastic packaging, personal protective equipment, and other disposable plastic protective equipment have led to a steady increase in solid waste and pollution on soil (Patrício Silva et al., 2021b). Plastics and waste masks affect the natural ecosystem and people's health (Patrício Silva et al., 2021b). Table 5 presents the generation and disposal of solids and the environmental impacts in selected regions of the world since the COVID-19 outbreak.

After the outbreak of COVID-19, the continuous increase in the amount of medical waste caused significant difficulties in managing plastic waste and even paralyzed the waste disposal system in many countries. Before the COVID-19 outbreak, medical waste and plastics were disposed of normally in accordance with each region's waste management regulations. These wastes were first sorted according to their characteristics, and sterilized. Then, most of the wastes were transported to designated sites for incineration and landfill, and some of the plastic wastes were recycled by sterilization technology (Khoo et al., 2021). However, the rapid spread of COVID-19, the high risk of infection, and the diverse modes of transmission have caused an increasing demand for medical devices in various countries (Tian et al., 2020), resulting in varying degrees of impacts on the management of medical waste. This is especially true in countries with larger populations, which have more urgent needs for medical devices and at the same time generate more solid waste. Therefore, Table 5 shows the used mask generation, disposal, and the associated environmental impacts of the top eight most populous countries after the COVID-19 outbreak.



Note (*): The downward direction of the arrow represents a decreasing level of water contamination. On the contrary, the upward direction of the arrow represents an increase in the level of water pollution.

Fig. 3. The variations of surface water pollution, coastal water pollution and groundwater pollution in different regions of the world during COVID-19.

Table 5

Impacts of COVID-19 on solid waste generation, waste disposal, and soil contamination.

Continents	Country	Population (approx.)	Total used masks (tonnes per day)	Urban population rate (%)	Total plastic packaging/shell (tonnes per day)	Total solid waste disposal (tonnes per day)	Solid waste disposal methods	Key findings	References
Asia	China	1,439,323,776	5619.12	61%	140.48	5759.60	Incineration	The usual way to dispose these solid wastes in China is to incinerate them and provide heat to generate electricity. However, during the COVID-19 pandemic, the continued increase in solid wastes resulted in increased waste incineration, but the heat from incineration was not fully utilized.	(Ma et al., 2020; Singh et al., 2020a)
	India	1,380,004,385	3091.21	35%	77.28	3168.49	Incineration	Before masks are incinerated, it is recommended that used masks be disinfected with a civilian standard bleach solution (5%) or sodium hypochlorite solution (1%) before they are placed in a closed bin and given to a designated company for incineration.	(Sangkham, 2020)
	Indonesia	273,523,615	980.31	56%	24.51	1004.82	Incineration and landfill	These solid wastes are sanitized and labeled as hazardous. These wastes are taken to a designated site for incineration or landfill.	(Sangkham, 2020)
	Pakistan	220,892,340	494.80	35%	12.37	507.17	Incineration	These solid wastes are burned in the open area. The burning releases large amounts of toxic gases and substances that pollute the air and soil.	(Khalid et al., 2021)
	Bangladesh	164,689,383	411.06	39%	10.28	421.34	Landfill	These discarded masks and other medical waste are dumped in large quantities in arbitrary places and are disposed of by untrained cleaning staff, and only a portion of the wastes are transported to the prescribed places for incineration. The pandemic has interrupted the activities of recovering and recycling of plastic waste, thus increasing the environmental pollution of landfills.	(Islam et al., 2020)
South and North America	Brazil	212,559,417	1197.13	88%	29.93	1227.06	Landfill	Before the outbreak of COVID-19, the disposal of these wastes in Brazil was resource recovery. However, after the COVID-19 outbreak, these materials were disposed of in landfills and required an additional volume of 19,000 m^3, which reduced the life of the landfills, with both economic and environmental losses.	(Urban and Nakada, 2021)
	United States	331,002,651	1758.29	83%	43.96	1802.24	Incineration and landfill	These solid wastes are handled as usual. However, the safety of the handling staff and the strict management of solid wastes are ensured.	(Sharma et al., 2020)
Africa	Nigeria	206,139,589	686.03	52%	17.15	703.18	Landfill	These wastes are dumped in and around landfills without proper disposal and it increases the risk of virus transmission.	(Oyedotun et al., 2020)

According to the analysis results in Table 5, we can find that among these eight countries, the highest average daily amount of used masks is generated in China, and the lowest is in Bangladesh. Among them, China produces about 5619.12 tonnes of used masks per day, India 3091.21 tonnes, the United States 1758.29 tonnes, Indonesia 980.31 tonnes, Pakistan 1197.13 tonnes, Nigeria 686.03 tonnes, and Bangladesh 411.06 tonnes. This is based on the acceptance rate of 80% of the population and the use of 2 masks per day. In fact, each country produces not only masks but also disposable gloves, disposable gowns, and other plastic waste every day. In addition, some plastic shell waste is generated due to the packaging of masks. According to the calculations in Table 5, China produces about 140.48 tonnes of plastic shells per day due to mask use, India produces the second highest at 77.28 tonnes, and the least is Bangladesh which produces 10.28 tonnes of plastic shell waste. Therefore, in terms of total mask waste, China has to deal with about 5759.60 tonnes per day, about 14 times more than Bangladesh and 11 times more than Pakistan.

In collecting and analyzing the literature, we found that during the COVID-19 pandemic, the disposal of the proliferating plastic wastes in all of these eight countries, except the United States and Indonesia, were affected to varying degrees. These plastic wastes are typically disposed of by incineration, landfill, or a combination of incineration and landfill, all of which are not well-equipped for resource recovery. Since viruses may contaminate these wastes, some countries also disinfect the wastes before incineration or landfill, which invariably increases the cost of waste disposal (Khoo et al., 2021). In addition, these wastes are not well treated in some countries. For example, in India, due to the overloaded solid waste management, these mask wastes and plastic shells were discarded around the garbage cans to pollute the surrounding environment and soil (Ganguly and Chakraborty, 2021). In Pakistan, these solid wastes were burned in the open, which released large amounts of toxic gases and substances to pollute the air and soil (Khalid et al., 2021; Shah et al., 2021). In addition, the increase in plastic wastes after the COVID-19 outbreak made it impossible to recycle them in Brazil. As a result, 19,000 m^3 of landfill had to be added, which seriously polluted the soil and damaged the ecosystem (Urban and Nakada, 2021). In China, since COVID-19 was first discovered in China and the number of infected people was high, the local government had to add many solid waste disposal centers to incinerate the plastic wastes and these wastes were not recycled effectively, thus causing environmental pollution (Sangkham, 2020; Singh et al., 2020a). Finally, in Nigeria and Bangladesh, these medical wastes were sent to the vicinity of landfills and dumped randomly without proper disposal, which increased the risk of virus transmission, as well as soil contamination and ecological pollution (Islam et al., 2020; Oyedotun et al., 2020). These masks and plastic shells are not biodegradable because the molecular bonding of their plastic structures makes them incapable of decay, and the low melting point of plastics would lead to the release of large amounts of harmful gases when plastic wastes are incinerated (Benson et al., 2021; Potrykus et al., 2021). Therefore, during the COVID-19 pandemic, solid waste management in different countries was affected to some extent due to the unprecedented growth of plastic wastes, which caused soil pollution and ecological damage.

7. Implications of COVID-19 on carbon emissions

During COVID-19 lockdown, many human activities stopped as a result of curfew; hence this caused a change in the emissions of carbon and other greenhouse gases around the world as reviewed in this section. The world energy report of 2020 by IEA stated that there was a decline of 3.8% of global energy demand which resulted in a 5% decline of global carbon emissions in the first quarter of 2020 as compared to that of 2019. There were also local changes in carbon emissions as discussed below.

7.1. Asia

A study was conducted for the Western Singapore straits on the carbon emissions from marine traffic during COVID-19 lockdown in 2020 which were compared to those in 2019 (Ju and Hargreaves, 2021). The results showed that carbon emissions of bulk carriers, container ships, tankers, and tugs ships increased by 15.7%, 1.3%, 6.15%, and 1.12%, respectively, in 2020 compared to 2019. In contrast, the carbon emissions of ferry, general cargo, passenger, and RoRo ships decreased by 75.82%, 0.84%, 28.35%, and 0.73% respectively, in 2020 compared to 2019. This is because non-essential travel was not allowed during the COVID-19 lockdown, hence a decrease in emissions due to lower ship trips. Another study was conducted in China to compare carbon emissions from fuel vehicles from 2018 to 2020 during and after lockdown (Zhang et al., 2021). The results showed that in February 2019, the CO_2 emission (in 10,000 tonnes) was 4045.19. The emission level dropped to 2363.82 in February 2020 but rose to 3409.97 in April 2020. The reason for the drop in February 2020 was the strict lockdown imposed by the Chinese government, which caused fewer vehicles on the road. However, the CO_2 emissions rose again after just 2 months due to effective pandemic control, leading to some provinces resuming activities. Another research was done in Xi'an, China to compare the carbon emissions before lockdown and during lockdown by directly measuring the CO_2 concentration in the atmosphere (Wu et al., 2021). The results showed that CO_2 concentration during total lockdown period (Feb 5 to Feb 21, 2020) was 7.5% lower than before lockdown period (Jan 25 to Feb 4, 2020).

7.2. Europe

A study was done at the Bournemouth University in UK to compare the carbon footprint on campus during lockdown (April–June 2020) and before lockdown (April–June 2019) (Filimonau et al., 2021). During lockdown, the carbon emissions dropped from 2140 to 1521 t of CO_2-eq. Additionally, the largest share of carbon emissions in 2019 was contributed by student and staff commute, followed by utilities. In 2020 during the lockdown, the largest share of carbon emissions was attributed to student and staff working from home activities. This was due to campus closure and online learning, which decreased commute and energy use around campus. Another research was conducted in France to determine the short- and long-term COVID-19 effects on carbon emissions using the Computable General Equilibrium Model. The results show that during the 55-day lockdown in 2020, the carbon emissions dropped by 6.6%; however, the drop was short-lived as carbon emission levels rose again after the pandemic (Malliet et al., 2020). Another study was done at the Algeciras port in Spain on the ships' carbon emissions during lockdown at the berth, and the results were compared with during their regular operation times. During lockdown, the daily carbon emission from ships was only 6.2 tonnes, while during normal operation, the level was 121.5 t (Durán-Grados et al., 2020).

7.3. North and South America

Research was conducted in Los Angeles and Washington DC/Baltimore areas in the USA to determine the CO_2 emissions change in 2020 lockdown compared to previous years by using atmospheric observations (Yadav et al., 2021). The results showed that in Los Angeles, there was a 0.57 MtC $\pm$ 0.30 MtC and 1.09 MtC $\pm$ 0.21 MtC reduction in CO_2 emissions during March and April of 2020 respectively as compared to previous years. Additionally, in Washington DC/Baltimore, there was a 0.45 MtC $\pm$ 0.25 MtC and 0.43 MtC $\pm$ 0.15 MtC reduction in CO_2 emissions during March and April of 2020 respectively compared to previous years. In Colombia, the emissions of the first half of 2020 during travel restrictions were compared with the those of the same period in 2018. The study found a decrease in 28% of CO_2 emissions during the COVID-19 period, which was mainly due to a decrease in the burning of fuels for transportation (Camargo-Caicedo et al., 2021).

7.4. Africa

In Egypt, based on the results of the carbon footprint method, the GHGs emissions during the curfew period from January to August 2020 reduced by 17% compared to the same period in 2019 (Madkour, 2021). The GHG emissions reduced due to the reduction of transport such as cars and aviation and reduction of energy use at workplaces due to stay-at-home policies.

7.5. Oceania

In New Zealand, air travel restrictions during COVID-19 lockdown caused a decrease in carbon emissions from airplanes from 250,000 $kgCO_2$-eq in August 2019 to almost zero in April 2020 but the emissions rose to 50,000 $kgCO_2$-eq in July 2020 due to the loosening of travel restrictions (Becken and Hughey, 2021).

Based on this section's review, it is evident that carbon emissions were reduced in different cities worldwide (Fig. 4), primarily due to less travel and less energy use in workplaces during the pandemic. The only rise in carbon emissions observed was due to the operations of essential ships such as bulk carriers and tankers that did not stop during covid-19 to keep the supply chains stable.

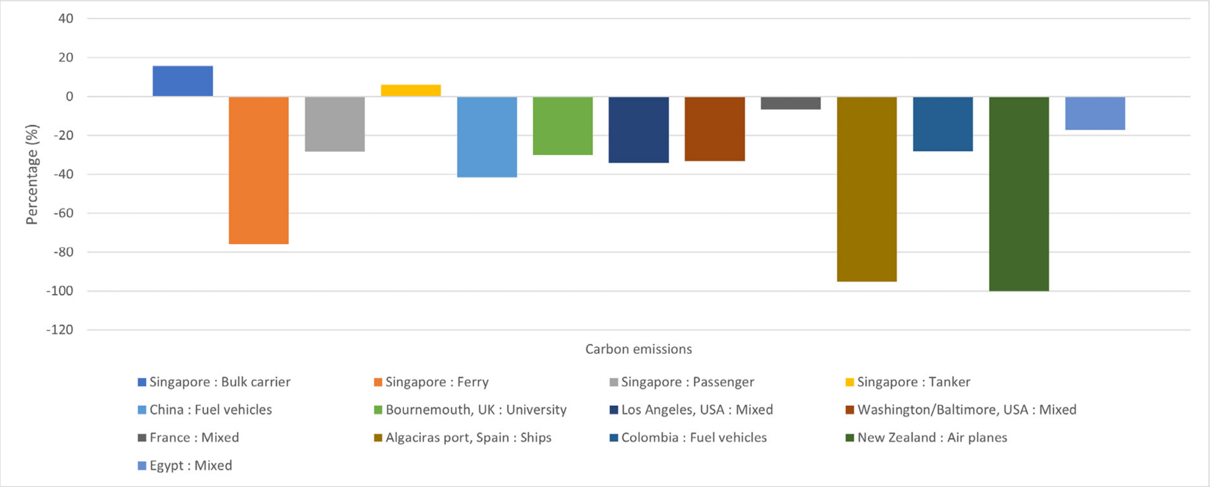


Fig. 4. Percent changes of carbon emissions around the world and their sources.

8. Strategies for future sustainability

Based on the previous evaluation of the data from literature, it is clear that the COVID-19 pandemic and its associated lockdown have had some impacts on the global environmental pollution and carbon emissions. Numerous studies have shown that COVID-19 has resulted in positive impacts on air and water pollution during the short period of lockdown. Nevertheless, when the restrictions were lifted, air and water pollution showed trends of deterioration. Meanwhile, soil pollution in the COVID-19 era seems to have worsened because of the large amount of plastic waste and protective equipment such as masks generated due to implementation of safety measures and the increased amount of household waste generated by people during home quarantine and travel restrictions. Therefore, it is necessary to prolong the environmental benefits on air and water from COVID-19 to improve future sustainability. At the same time, since COVID-19 has negative impacts on soil pollution, it is essential to reduce the worsening of soil pollution problems through appropriate measures and strategies. Last but not least, carbon emissions have also decreased during COVID-19 era. This would be beneficial for many countries to achieve the goals of the Paris agreement and to achieve sustainability. Maintaining this improvement is also a subject of consideration for governments as well as municipal residents. The following subsections suggest a number of specific strategies to prolong the benefits of COVID-19 on air, water and carbon emissions as well as to tackle the negative impacts of COVID-19 on soil pollution.

8.1. Strategies for air and water pollution

The unexpected outbreak of COVID-19 has led to an unprecedented and widespread shutdown of agriculture, industry and commercial activities around the world. Due to the COVID-19-related restrictions, governments around the world are beginning to realize that air and water pollution can be gradually mitigated. Strategies that can prolong the benefits of COVID-19 to air and water pollution comprise:

(i) National governments need to establish laws and regulations to control air and water pollution during COVID-19 and after the end of the pandemic. For example, regional governments can enact environmental tax laws to impose higher taxation on pollutants. At the same time, policymakers can consider increasing tax rates in low-tax areas and strengthening tax incentives to stimulate enterprises to achieve pollutant emissions reduction (Li et al., 2021). Governments likewise can formulate policies that disincentivize motorized modes of transportation particularly in urban areas, while rewarding non-motorized modes (Othman and Latif, 2021; Ravindra et al., 2021). Zhou et al. (2021) suggest that further improvements to the water pollution issue can be achieved in accordance with the Water Pollution Control Action Plan (i.e., the "10-point Water Plan").

(ii) Strengthening the environmental monitoring system. The establishment of a National Ambient Air Quality Monitoring Network (NAAQMN) will allow a better understanding of the relationship between emissions and air pollution patterns, and enable improved air quality management. An international three-dimensional monitoring strategy has been proposed to characterize the three-dimensional distribution of atmospheric constituents to reduce uncertainty and facilitate diagnostic understanding and prediction of air pollution (Liu et al., 2021a; Liu et al., 2021b).

(iii) Applying new science and technologies to further reduce air and water pollution. Research has demonstrated that using new technologies to improve industrial efficiency can significantly reduce reliance on coal-fired power generation and thus reduce air pollution problems (Yue et al., 2021). Meanwhile, the utilization of nanostructured adsorbents and phytoremediation-related methods can effectively reduce various pollutants in sewage, and the combination of microorganisms and aquatic plants (microbe-integrated phytotechnology) is also a prospective technological method (Hu and Li, 2021; Zamora-Ledezma et al., 2021).

8.2. Strategies for soil pollution

Soil pollution was further exacerbated by the massive amount of municipal solid waste and medical waste generated during the pandemic as a result of home quarantine. It is urgent to adopt control and management measures for solid waste and medical waste. The various governments should establish a waste management system that is reliable and can ensure an inclusive approach for all stakeholders. Policymakers ought to impose serious restrictions on the disposal of hazardous waste, the amount of waste that can be released into the environment, the definition and classification of hazardous and non-hazardous substances, and the perfection of laws related to incineration and other less centralized waste disposal methods (Das et al., 2021a; Torkashvand et al., 2021). Training the formal workforce and adding integrated measures such as automated or mobile incinerators to develop a highly resilient Soil Pollution Treatment System is also an effective strategy (Ganguly and Chakraborty, 2021). Meanwhile, in the era of COVID-19, the use of "sterilization wave" technology is helpful in the treatment of medical waste. Autoclave treatment not only helps reduce the risk of exposure to infectious medical waste, but also reduces the weight of the waste and consequently the burden of soil contamination (Das et al., 2021b; Zhao et al., 2021). While increasing the recycling efficiency of solid waste, it is also necessary to take some scientific and professional measures (e.g. microbial degradation of waste) to reduce the negative impacts of solid waste and medical waste on the environment (Patrício Silva et al., 2021a).

8.3. Strategies for carbon emissions

Available studies show that the pandemic contributed to a substantial decrease in carbon emissions. This is beneficial for the sustainability of development in many countries and the achievement of the Paris Agreement targets. However, preventing a retaliatory increase in carbon emissions after COVID-19 is an additional challenge as well. First of all, the green economy recovery plan is worthy of global attention. Promoting energy-efficient technologies and strengthening R&D on energy-saving technologies to improve the utilization of energy are important approaches to reduce carbon emissions. There is also a need for more clean and renewable energy in the current energy system. In fact, there is great potential for the development of sustainable resources and renewable energy infrastructure to prolong the beneficial impacts of COVID-19 on carbon emissions. Governments should establish short-term policies and develop medium- and long-term operational schemes to attain specific renewable energy targets (Hoang et al., 2021b). In the long term, governments are encouraged to promote trade openness, as adherence to free trade will help achieve global emissions reduction targets. The regulatory adjustments needed to achieve sustainable reductions in carbon emissions may include: imposing minimum energy efficiency standards on residential buildings, implementing zero carbon emission targets for new buildings, limiting access to clean air areas for highly polluting vehicles, banning the sale of new diesel and gasoline vehicles (Li and Li, 2021; Wang and Wang, 2020; Wang et al., 2021). Secondly, carbon emissions reduction can also be achieved by adopting an optimal structure of travel. Carbon footprint studies have shown that emissions can be easily reduced by replacing air travel with high-speed railway travel. Since the reduction in ultrafine particle and black carbon concentrations is related to the reduction in traffic flow, the control of traffic flow in and after the COVID-19 era is also an effective approach (El Geneidy et al., 2021; Hudda et al., 2020).

9. Conclusion

This article reviews the variations of global environmental pollution and carbon emissions during the COVID-19 pandemic to determine the specific implications of COVID-19 on these domains. In terms of air pollution, air pollutants (such as NO_2, and CO) all experienced noticeable decreases during the pandemic. It is worth mentioning that $PM_{2.5}$, PM_{10}, O_3 and SO_2 were on the increase in some countries and regions. O_3 has even increased significantly in the French Lyon region compared to the past. SO_2 level also demonstrated uptrend in France (Lyon), UK, India (Kolkata), Peru, Spain (Barcelona) and Malaysia (Kuala Lumpur). Although there was a slight increase in some air pollutants, the global air pollution was considerably mitigated generally. Pollution of surface water, coastal water and groundwater has experienced a downward trend during the pandemic. Heavy metal concentrations, *E. coli* levels, and chl-a concentrations in water bodies have all declined, and indicators of water contamination (e.g., K_d (490), HPI, and DO) improved in values. However, it is worth noting that some reservoirs experienced green algal blooms due to improper management during the pandemic, and some of the coastal waters have plastic and chemical contamination due to the mismanagement of large amount of PPE waste. The problem of soil pollution was further exacerbated during the COVID-19 period because of the large amounts of municipal solid waste and PPE (such as masks and gloves) generated as travels were restricted. Meanwhile, the disposal methods (incineration, landfill or a combination of incineration and landfill) of municipal solid waste as well as medical and PPE wastes have not been very effective, and there was a lack of resource recycling. Since viruses could contaminate these wastes, some countries also disinfected the wastes before incineration or landfill, which at the same time increased the burden of waste disposal and thus further worsened soil contamination. Carbon emissions were temporarily mitigated during COVID-19, as were air and water pollution problems.

The continual improvement of air and water pollution in the post-COVID-19 era can be achieved through a series of government policies and regulations (e.g., environmental taxes on enterprises), the construction of a more comprehensive air and water environment monitoring system, and the use of new scientific technologies (e.g., industrial efficiency technologies for air pollution, nanomaterial adsorption technologies and microbial remediation methods for water pollution) to prolong the benefits of COVID-19 on air and water pollution. A sustainable strategy for amelioration of soil pollution could be the adoption of mandatory management measures for solid and medical wastes, and the establishment of a reliable waste management system. Integrated measures such as automated or mobile incinerators and specialized measures such as "sterilization wave" technology can reduce the negative impacts of COVID-19 on soil pollution relatively quickly. The sustainable strategies to maintain the gradual reduction of carbon emissions include the development of energy-efficient technologies to improve energy utilization and the optimization of travel structure and strict control of traffic flows.

Furthermore, COVID-19 pandemic could have profound impacts on the global environmental health and human health. Based on this review, the pandemic is expected to continue to lessen the air and water pollution problems, resulting in cleaner air and water. Improved air and water quality could lead to lower risks of human illnesses and improved health. The increase in soil pollution caused by the COVID-19 closure will further increase environmental health problems, while the reduction of indoor air quality as a result of lockdown would also affect human health. Therefore, it is evident that COVID-19 yields both positive and negative impacts on environmental and human health.

Future research work could focus on the changes in the global environmental pollution and carbon emissions after the pandemic is completely under control. Future work could also investigate the impacts of modifications in human lifestyles on pollution and carbon emissions after the outbreak is successfully controlled. This literature review comprehensively presents a systematic overview of the variations in global environmental pollution and carbon emissions during the COVID-19 period which contributes to the formulation of specific strategies to prolong the positive impacts and minimize the negative impacts of COVID-19 for future sustainability.

CRediT authorship contribution statement

Mingyu Yang: Writing – original draft. **Lin Chen:** Writing – original draft. **Goodluck Msigwa:** Writing – original draft. **Kuok Ho Daniel Tang:** Conceptualization, Writing – review & editing. **Pow-Seng Yap:** Conceptualization, Writing – review & editing.

Declaration of competing interest

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

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