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Review article

The implications of COVID-19 in the ambient environment and psychological conditions

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ABSTRACT

The COVID-19 pandemic caused by SARS-CoV-2 has posed a huge threat to mankind, deeply endangering healthy states and influencing economic development. COVID-19 has important impacts on the environment as anthropic interventions to nature has been largely reduced after almost all countries implemented partial or complete blockade to curb the spread of the virus. Up to now, a series of studies have focused on the relationship between COVID-19 and the environment from different cities. In this review, we summarized the latest data on the correlation between COVID-19 and environmental changes. As a result, imposing necessary restrictions can help suppress the virus chain while improving air quality in some countries. The significant reduction in NO2 emission, PM2.5 level and other hazardous factors reflected the promising consequence of the efforts made during the lockdown period. It is, sometimes dark clouds have silver linings. It is worth noting that along with these positive outcomes, secondary pollutants such as ozone, however, remained unchanged or even increased significantly. Additionally, medical wastes and plastics pollutants would be increased substantially. The extensive use of masks in daily life and other medical materials is bound to increase the burden of waste disposal and environmental degradation. For the general public, in addition to the physical lesions caused by SARS-CoV-2, confirmed/suspected cases and even the normal group may suffer from mental problems. Based on those mentioned impacts, the way forward depends largely on our attitude and decision. It is indispensable to assess potential deleterious effects and to take preventive measures in time to respond to the post-pandemic era. In this way, potential silver linings will not become temporary.

1. Background

In late December 2019, pneumonia with unexplained pathogenesis appeared in Wuhan, China. In the beginning, due to unclear causes, this disease was exploded without timely control and prevention. Because of the upcoming Chinese Lunar New Year festival, China underwent a mass migration inter and intra the countries in a short framework. The number of the infected increased rapidly, and the scope of infection was expanded sharply. Now it has occupied nearly the whole world. This new type of pandemic disease has been officially named by the World Health Organization (WHO) as COVID-19 (coronavirus disease 2019). And its virus has been meanwhile termed as SARS-CoV-2 (severe acute respiratory syndrome coronavirus 2) (WHO, 2020a).

SARS-CoV-2 tears around the world and the outbreak of COVID-19 has attracted global attention. Although SARS-CoV-2 belongs to the same Betacoronavirus genus as the coronaviruses responsible for the severe acute respiratory syndrome (SARS) and the Middle East respiratory syndrome (MERS), there are still several differences between them, including infection rate and lethality. The clinical symptom of the novel virus-induced COVID-19 is characterized by a respiratory syndrome with a variable degree of severity, ranging from a mild upper respiratory tract illness to severe interstitial pneumonia and acute respiratory distress syndrome (ARDS) (Mo et al., 2020; Petrosillo et al., 2020). Moreover, non-typical symptoms cannot be neglected due to complicated and unclear pathogenetic features, such as loss of the sense of taste in some patients, and asymptomatic infection.

On January 30, the WHO declared it as a Public Health Emergency of International Consequence (a global emergency health event) (WHO, 2020b). According to data from Johns Hopkins University and WHO, the COVID-19 pandemic has affected more than 200 countries and regions, as of 9:33 am CET, 27 December 2020, there have been 78,267,552 confirmed cases of COVID-19, including 1,737,339 deaths, reported to
Controlling the spread of the coronavirus and reducing mortality are the most important tasks to be done. On 23 January, China strictly implemented an unprecedented lockdown measure in Wuhan to curtail the spread of the virus. All modes of transportation were stringently prohibited to enter and leave Wuhan. Citizens were asked to stay at home, except for outdoor necessary activities. In this case, only one member can be allowed to go out to buy necessities per family per day. Additionally, people spontaneously used tree stumps and large rocks as temporary barriers to restrict outsiders between neighboring communities (The New York Times, 2020).

With the rapid increase in cases in various countries, different governments announced and implemented partial or complete blockade measures, including Italy (Chintalapudi and Battineni, 2020), France (Roques et al., 2020) and India (The Lancet, 2020). Due to the closure of borders in different nations, all unnecessary activities have been banned and almost all flights have been canceled. The most pronounced phenomenon is that global air quality has been improved in this special period.

As nearly all transportation systems and industrial factories were required to shut down, a sudden drop in carbon emissions has been observed. In China, coal usage was reduced by 40% since the last quarter of 2019, and emissions data showed a 25% reduction at the beginning of this year (BBC, 2020). According to the report of the Ministry of Ecology and Environment of the People’s Republic of China, the average percentage of days enjoying good air quality per year is about 83.5% with a 6.6% increase year-on-year based on the data of a total of 337 cities (MEEC, 2020). Compared with the same period last year, the level of CO2 in New York has dropped by nearly 50% (BBC News, 2020). Also, the long-lost transparent and clear sky can be seen again in some Indian heavily-polluted areas (CNN, 2020a). Due to lockdowns in various places, energy distribution and consumption have been changed, and emissions have been slumped, which contributed to the improvement of air quality in most parts of the world. The significant reduction in some atmospheric gases and urban particulate matter reflected the promising consequence of the efforts made during the lockdown period. Imposing necessary restrictions can help suppress the virus chain while improving air quality in some countries.

Lockdowns have brought out opportunities for atmospheric improvement, however, the results are still not free to the uncertainties. Furthermore, along with these positive outcomes, adverse effects are obvious, such as exponential increase in deaths, widespread unemployment and economic standstill. In terms of the environment, secondary pollutants, such as ozone and other environmental aspects seem not optimistic (Sicard et al., 2020; Siciliano et al., 2020). Additionally, the drastic increase in medical wastes, including disposable masks, medical protection suits and sanitizer bottles would intensify the burden in the disposal of hazardous materials that are potential threats to the ecosystem (UN, 2020). Apart from the natural environment, the social environment and self-identity can also be affected during this sudden pandemic (Huang and Zhao, 2020; Sher, 2020). Mental health is an emerging problem that should be more centralized and conquered, as unemployment, social isolation and social turbulence would aggregate phycological states during this tough period.

Therefore, understanding the relationship between the COVID-19 pandemic and the environment is extremely important, which not only helps to investigate the potential changes in atmospheric chemistry, but also provides useful and timely information for decision-making as well to fight the post-pandemic era. This review aimed to discuss the impacts of COVID-19 on the ambient environment according to recent literature and reports. Not only highlighting the beneficial effects of COVID-19 on our ambient environment, but adverse outcomes are also discussed to help policy-making and to ensure a cleaner environment. From this pandemic, it is imperative to schedule regulations that will be put into place to help build a cleaner ambient environment with better social conditions. To achieve this, we need to seize a small portion of opportunities that have emerged. Experiences and lessons should be summarized, and appropriate policies should be actively formulated to protect public health and prevent post-pandemic deterioration.

2. Effects of COVID-19 on atmospheric gases

A variety of pollutants (such as NOx, COx, SOx, and particulate matter) produced by coal-burning and plants can cause ecosystem degradation (Pandey et al., 2005; Wu and Zhang, 2018). The adverse effects of these pollutants on humans and other species have been extensively studied (Crouse Dan et al., 2015; Olaniyan et al., 2020; Weinmayr et al., 2010). Cleaner air seems to be a silver lining from the lockdown of the COVID-19 pandemic, during which a series line of important measures taken and efforts paid, such as implementing compulsory social distancing, and quarantining suspected cases, as well as isolating confirmed patients, exhaust emissions and traffic burden were substantially lessened.

Most information on air pollutants in different areas was released by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Plus, several studies have collected pollutant data from the ground monitoring systems and concluded that the environmental quality has been drastically improved after the COVID-19 lockdown.

2.1. Nitrogen oxide (NOx)

High levels of NOx and particulates are culprits for haze formation, especially in the heavily-polluted areas in winter-and-spring. NO2 and NO mainly originated from the combustion of coal and foils and traffic exhausts. They can actively react with other pollutants in the air to induce secondary pollutants, such as acid rain and ozone which are also risk factors for ecosystem imbalance. Therefore, NO2 emissions are one of the threatening pollutants in the air and are considered an important part of atmospheric pollutants (Collart et al., 2018; Zhao et al., 2020a). In addition, NO2 is a representative of NOx and a crucial indicator of air quality, which is extensively monitored by different organizations around the world (Lu et al., 2020).

From recent studies and reports, most data of satellite monitoring images about NO2 information are from NASA, who used ozone monitoring instrument (OMI) on the launched Aura satellite to collect data; and ESA, where Copernicus Sentinel-5P satellite was employed to track different types of pollutants in the atmosphere (ESA, 2020a; NASA, 2020a). The visible diminishment of NO2 emissions during the lockdowns can be identified by images and information issued by NASA and ESA. As a result, environmental data from NASA indicated that Wuhan city (Figs. 2 & 3) and the U.S. have experienced approximately 30% of decreases in NO2. Also, the imagery data released by ESA with regard to the countries of France, Italy and Spain (Figs. 3 & 4), showed that NO2 levels were differentially changed, with about 20–30% of reductions, after the comparison between March 2019 and 2020 (ESA, 2020b, 2020c). For the entire European areas, a magnificient drop can be seen in the average level of NO2 (ESA, 2020c).

Throughout the pandemic, NO2 concentration in China dropped significantly (NASA, 2020a), which is probably related to the large-scale shutdown of industrial factories and reduced consumption of coal and fossil fuels (Patil, 2020). Relative to the average level from 2015 to 2019, NO2 experienced a significant decline in central and eastern China. This reduction initially took place near Wuhan, the central city of China, and then extended to impact other parts of China (Wang and Su, 2020). Similarly, ESA has tracked and reported the concentration of atmospheric NO2 in China. The imagery data showed that the nationwide NO2 density was significantly lower after lockdown (February 2020) than that of the previous period (January 2020), which may be explained by the restriction measures taken, such as the closure of industries and constructions, and strict limitation of human mobility (Wang and Su, 2020).
Fig. 1. Current distribution of COVID-19 in different countries. A. Bubble map of confirmed cases across the world. B. Bubble map of deaths distribution around the world. C. Distribution of confirmed cases and the weekly increased numbers in different areas. D. Distribution of death tolls and the weekly increased numbers in different areas. (Source: World Health Organization, 2020a, 2020b, 2020c, 2020d, 2020e, 2020f, Accessed date: 9:33 am CET, 27 December 2020, there have been 78,267,552 confirmed cases of COVID-19, including 1,737,339 deaths, reported to WHO). https://covid19.who.int
In addition, Kanniah and co-workers employed the data of tropospheric NO$_2$ column number density by the Dutch-Finnish OMI sensor on board Aura satellite, and the analysis showed that a 27%–34% reduction of tropospheric NO$_2$ occurred in the detected area in Southeast Asia. Moreover, they analyzed the data of NO$_2$ concentrations from different ground stations. The ground-based measurements suggested that there was a 33–46% of reduction in NO$_2$ level in the industrial regions, and 64% in the urban areas, respectively (Kanniah et al., 2020).

In India, due to the sharp increase of infected patients, strict lockdown measures have been adopted since March 25, 2020 to prevent the spread of COVID-19, which contributes to a palpable reduction in NO$_2$ emission, especially in Delhi and Mumbai where there was a 40 to 50% reduction after the lockdown period between March 25, 2020 to April 20, 2020, compared to the same period last year. Furthermore, the satellite data from ESA suggested that air quality has improved in the Indian territory in the aspect of NO$_2$ emission (Shehzad et al., 2020; ESA, 2020d). The dynamic values collected in different monitoring stations in Delhi and Mumbai also authenticated this phenomenon. In Delhi, the level of NO$_2$ emissions were significantly dropped from 30 to 65 μg/m$^3$ to the level of 12–25 μg/m$^3$ after lockdown. Similarly, there was an observable decline in Mumbai, from the level of 28–62 before to 8–15 μg/m$^3$ post. Apart from the urban area, the NO$_2$ level has also declined at the Maritime Route of the Indian Ocean, where the ship transportation faced a slump. Collectively, the reduced energy consumption during the outbreak may be an important cause for the drastic decrease in NO$_2$ emissions in India (Shehzad et al., 2020).

Berman and Ebisu studied the changes in atmospheric chemistry in the U.S. and reported a 25.5% of reduction (Absolute value: 4.8 ppb) in NO$_2$ across America during the COVID-19 pandemic (March 13–April 21) as compared to the historical data (2017–2019). In addition, PM2.5 level as well experienced a decrease but the extent was less than that of NO$_2$. The ground monitoring data were similar to the satellite data provided by NASA which suggested that NO$_2$ was reduced by around 30% during March in the northeastern urban area, compared with the

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Fig. 2. A & B. NO$_2$ emissions in China before and after lockdown (NASA, 2020a). The left image A shows the average concentration in Feb 10–25, 2020, while the right image B shows the average concentration measured in Jan 1–20, 2020. C. NO$_2$ emissions in Wuhan during 2019 and 2020 (NASA, 2020a).
same period last year. The reason underlying the phenomenon that the percentage change of NO$_2$ is greater than that of PM2.5 could be ascribed to the fact that apart from multilayer transportation emissions, PM2.5 can also come from indoor activities, such as cooking-derived particles and biomass burning. Especially during this special time, nearly all the population stays at home most of the time, and household emissions have thus increased dramatically (Berman and Ebisu, 2020).

Looking at the Europe, cities like Rome, Madrid and Paris in Europe also experienced different extents of decline in NO$_2$ level (average data based on 14–25, March 2020) in comparison to the monthly average data of March 2019 (Zambrano-Monserrate et al., 2020). In Madrid and Barcelona, two largest cities in Spain, it has been covered that the drastic reduction in human activities exerts a clear impact on air quality. The hourly observations of NO$_2$ were decreased by 62% and 50% respectively in Madrid and Barcelona through the lockdown (Baldasano, 2020).

However, it is still necessary to pay attention to the rebound effect after the pandemic. Since February 10, 2020, China has resumed the opening and operation of a series of necessary industries and enterprises. Since then, the monitored image data displayed that various pollutants rebound to varying degrees after the recovery of industrial factories and production. Therefore, taking China as an example, we can get a lesson that quarantine/isolation is an effective way to curb the spread of SARS-CoV-2, and it is also a catalyzer to improve air quality. But it should be still noted that the benefits are probably temporary since the phenomenon of NO$_2$ level bouncing back has occurred after expediting the recovery of production (Fig. 5). Presumably, once upon large-scale factories reopen, the emissions and exhausts probably tend to bounce back with the production moving on (Wang and Su, 2020; NASA, 2020b).

**Fig. 3.** Changes in NO$_2$ levels in different countries, including China (A-D), Italy (E-H) and the U.S (I-J). A-D: Source (ESA, 2020e). E-H: Source (ESA, 2020f). I-J: Source (NASA, 2020c).
2.2. Carbon dioxide (CO$_2$) and carbon oxide (CO)

One of the silver linings in this devastating situation is a reduction in emissions due to the decline in energy demand, including greenhouse gases (GHGs) and local pollutants. The carbon footprint (CF) indicator representative of energy consumption can indirectly reflect the release of GHGs. Recently, Rugani and Caro attempted to use this index to evaluate the impact of partial lockdown on the environmental consequences in Italy. After the analysis and calculation of CF in the lockdown period (March and April) and analogous periods from 2015 to 2019, it is estimated a 20% saving of CF on average during the lockdown period. However, in the most pessimistic case of gross domestic product (GDP), the estimated CF value by the end of 2020 will exceed the level of 2015, 2016, 2017 or 2018 (Rugani and Caro, 2020).

According to Wang and Su’s research, coal consumption and crude oil demand dramatically plummeted during the lockdown in China.

Fig. 4. NO$_2$ concentrations over Europe in the last year 2019 and same period of this year, 2020. The top image in the slider shows the average concentration in March-April of 2019, while the bottom image in the slider shows the average concentration measured in March-April of this year. Source (ESA, 2020b).
Compared with the two weeks after the Spring Festival last year, CO$_2$ emissions during the same period this year have been greatly reduced. Reduced at least a quarter of carbon emissions, equivalent to about 1 million tons, accounting for about 6% of global emissions in the same weeks (Wang and Su, 2020). It is reported that CO$_2$ emissions dropped by about 18% during February and March 2020 in China, with a considerable reduction in the consumption of carbon source by about 250 million tons. A similar phenomenon has been noticed in Europe, due to the lockdown, it is predicted to reduce carbon sources by approximately 390 million tons. The United States has been experiencing a reduction of CO$_2$ emissions to ~40% (Paital, 2020).

Gillingham and coworkers have focused on the short-run and long-term effects of COVID-19 on energy and the environment from a micro-level perspective. The authors pointed out that although the short-time mitigation in air pollution brings benefits, lives saving from near-term air cleaning can hardly offset the direct life loss caused by the COVID-19 in the U.S.. For example, the CO$_2$ emission was reduced by 15% in the U.S., and local air pollution, including SO$_2$, NOx, volatile organic compounds (VOCs), and urban particulate matter (UPM), seemed to be lightened that helped save about 200 lives per month. But since from COVID-19 pandemic, it has been a lot of deaths in the U.S.. Confronted by this huge number of deaths, the number of savings by the improvement of air quality is just a small consolation. From the long-term aspect, delays caused by the COVID-19 pandemic in the development and application of renewable energy would predictively result in an additional 2500 million metric tons of CO$_2$ emissions from the year 2020 to 2035, within which increased air pollutants would bring about approximately 7500 deaths. Collectively, their findings suggested that the adverse effects exerted by postponing all renewable resources investments even by one year would not be sufficient to counteract the silver linings from this pandemic (Gillingham et al., 2020).

Apart from the changes in CO$_2$, it can be concluded from the data provided by the Spatio-temporal satellite, that there was a slight reduction in CO level worldwide (< 0.03 mol/m$^2$) after shutdown in comparison to the conditions before. CO concentration in Delhi, Northern India plunged significantly during the lockdown period (March-April 2020). However, looking at the northern hemisphere, a slight increase (0.04 to 0.05 mol/m$^2$) in CO was observed this year relative to the same days in 2019 (Lal et al., 2020).

In China, the quarterly average (Januray-March 2020) of the CO level was 1.5 mg/m$^3$ this year. There was a year-on-year decline of 6.2% in CO concentration (Fig. 6). For SO$_2$, the average concentration was 11 $\mu$g/m$^3$, down 21.4% year-on-year, while O$_3$ concentration on average was 105 $\mu$g/m$^3$ without an obvious fluctuation in comparison to the same period last year. For atmospheric particulate matter, PM2.5 level dropped down by 14.8% with a quarterly average concentration of 46 $\mu$g/m$^3$ this year. PM10 concentration was 66 mg/m$^3$ averaged on the data within the first quarter, following a 20.5% year-over-year decline (Wang and Su, 2020; MEEC, 2020).

In Malaysia, through the data collected from different ground stations, it can be summarized that there is a slight decrease of SO$_2$ and CO emissions in urban and suburban areas, while the O$_3$ level has no significant changes in the lockdown period as compared to the same days before (during 18 March – 22 April 2018 and 2019). (Kanniah et al., 2020).

By obtaining and analyzing the monitoring data from stations in Rio
de Janeiro, Brazil, Dantas and colleagues concluded that starting from March 23, 2020, the reduction of population movement and traffic burden during the partial blockade has led to a decrease in CO and NO$_2$ levels, of which CO has a larger reduction than NO$_2$. On the contrary, O$_3$ concentrations showed an increase simultaneously (Dantas et al., 2020).

The above-mentioned preliminary analysis shows that GSGs emissions in most cities would experience reductions. During the coronavirus pandemic, global CO$_2$ emissions experienced an unprecedented drop by 17%. It is noted that with a lot of uncertainties, the observed signs may be temporary, and the long-term effect remains unclear. Although falloff in several types of pollutants can be seen in some countries amidst the pandemic, GHGs, the drivers of greenhouse effects/global warming, may rebound quickly with the recovery of economic and social activities.

2.3. Sulfur dioxide (SO$_2$)

SO$_2$ mainly comes from the burning of fossil fuels in power plants and industrial facilities. Also, other small portion of sources includes natural resources and heavy sulfur fuels in locomotives, ships, and other vehicles (EPA, 2020). Interaction between SO$_2$ and other ambient chemicals can cause acid rain, putting threats onto the already sensitive...
ecosystem. Additionally, SO₂ can react with other pollutant compounds in the air to form small particles and can be adsorbed onto the surface of particulate pollutants. These interactions and adsorption can cause and aggravate particulate pollution. For public health, short-term exposure to SO₂ potentially damages the respiratory system and makes breathing difficult. Long-term exposure is closely related to multiple pulmonary diseases when a sufficient amount of gas reaches the lung area (Kobayashi et al., 2020; Nascimento et al., 2020).

A recent study by Bao and Zhang employed data on human mobility and daily air pollutant concentrations to detect the relation between urban migration and air quality. A total of 44 cities in China were involved and all data were collected from Baidu between the period from 1 January until 21 March 2020. Accordingly, after quantitative analysis by utilizing long dynamic panel models, it illustrated a 7.80% of reduction in air quality index (AQI) and substantial improvement of air quality. Specifically, different extents of reduction in the daily levels of five air pollutants have been shown, 6.76% for SO₂, 5.93% for PM2.5, and 13.66% of reduction for PM10, as well as 24.67% for NO₂ and 4.58% of decline for CO. After strict enforcement of the travel ban, human activities dramatically slumped by 69.85%. Thereinto, after the analysis, the decreases in AQI, PM2.5, and CO are partially related to the stagnant mobility, and the potential causes for declined levels in SO₂, PM10, and NO₂ can be completely attributed to the reduced human activities (Bao and Zhang, 2020).

Lately, a study focused on the relationship between changes in pollutants and their sources to discuss how air quality correlates with emission reductions from different origins, including vehicle exhausts and industrial sectors. In addition, the authors intended to investigate which kinds of pollutants are mostly affected during the lockdown and which is the main cause/source responsible for atmospheric quality improvement. By collecting data from different ground stations from 366 cities in China, it can be observed that the averaged concentrations of PM2.5, PM10, SO₂, NO₂, and CO showed decreased trends compared with the levels before population control. More concretely, PM2.5 decreased from 65.0 μg/m³ to 51.4 μg/m³ and the decline trend was supported in 315 cities out of the total of 366 candidates. 331, 309 and all of 366 cities were observed to experience reductions in CO, SO₂ and NO₂, by averages of 0.23 mg/m³, 2.2 μg/m³, and 19.4 μg/m³, respectively. Mechanistically, the reason for the decreases in PM2.5, CO and NO₂ could be attributed to limited transportation and decreased industrial activities. And the decline in SO₂ level was probably due to the closure of almost all secondary industries during the restriction period (Wang et al., 2020).

After the lockdown period, some places have witnessed changes in ambient chemistry, which may distinctly vary from area to area. In Almaty, Kazakhstan, after collecting, analyzing and comparing related data between days during lockdown (March 19 to April 14, 2020) and identical days before restrictions (2018–2019), researchers found that PM2.5 concentration on average was reduced by 21% during the lockdown in comparison to the average level on the same period from 2018 to 2019. After comparing pre-lockdown (March 2 to March 18, 2020) and during lockdown (March 19 to April 14, 2020), the concentration of CO and NO₂ decreased by 49% and 35%, respectively, which may be due to traffic restrictions and seasonal weather change. Meanwhile, based on the reference conditions before the lockdown, a 7% increase in SO₂ concentration was concluded during the lockdown but it was not statistically significant. In this case, SO₂ levels are more closely related to household burning and coal combustion instead of traffic emissions (Kerimray et al., 2020).

2.4. Ozone (O₃)

As a particularly crucial trace gas, O₃ plays two-side roles, dependent on where it exists: it will increase GHGs, thus keeping the earth warm at the ground level; in the upper tropospheric atmosphere, it helps block ultraviolet rays of the sun from reaching the earth and shield us protection. O₃ is not directly discharged into the air, but instead, it is produced by the chemical reaction between NOx and VOCs. The VOCs/NOx ratio determines the chemical framework that affects ozone production (Zhang et al., 2020). It is generally recognized that the exhaust gas emitted by transportation, industrial sectors, and chemical plants reacts chemically with other existing air components to form ozone in the sunlight. On the minus side, O₃ is related to respiratory diseases. It has been authenticated that O₃ exposure increases susceptibility to asthma and adverse pulmonary events (Luo et al., 2020; Niu et al., 2020; Pepper et al., 2020).

Lately, Sicard and co-workers aimed to discuss the role of lockdown in the variations of NOx, PM2.5, PM10, and O₃ in four European cities of Nice (France), Rome and Turin (Italy), Valencia (Spain), and one Chinese city, Wuhan. The hourly pollutant levels were collected from different monitoring stations. It was observed that NOx was substantially reduced after stringent controls in all monitored cities. For UPM, the reduction was much more prominent in Wuhan (~42%) than in other tested cities (~8%). The decrease in UPM in European cities of less than 10% can be explained by the fact that reduced emissions from outdoor activities have been partially compensated by emissions from household activities, including biomass burning and cooking-related particulate matter. Although NOx and UPM have experienced favorable amelioration, the O₃ concentration has increased in all tested cities. The outcome of the elevation in O₃ concentration may be ascribed to a lower NO titration on account of a considerable decrease in NOx emissions (Sicard et al., 2020).

In China, NOx showed a dramatic decrease amid the control period, whereas averaged O₃ concentration was increased from 39.0 μg/m³ to 59.1 μg/m³. The authors explained that increases in O₃ during lock-downs may be related to decreased levels of fine particles. The lower UPM concentration would result in poorer absorption of other chemicals and thus keep them persistently suspended in the air, including hydro-peroxide radicals, causing an increase in O₃ production mediated by peroxy radicals (Wang et al., 2020). Similarly, in Almaty, Kazakhstan, there is a 15% increase in O₃ concentration. The authors explained that it could be due to intense solar activity during the restriction bans (Kerimray et al., 2020).

To evaluate the imposed measures on air quality variations over the Yangtze River Delta (YRD) Region, the WRF-CAMx model combined with monitoring data were employed. Overall, there are different decreases in concentrations of PM2.5, NOx and SO₂, and VOCs as well, while ozone does not show any decline but increases greatly during the stringent lockdown period. Through the results of source apportionment, it can be clearly illustrated that PM2.5 mainly derives from industrial and residential emissions, followed by mobile and dust in the YRD region (Li et al., 2020).b

In a recent study focusing on western Europe, the authors employed WRF-CHIMERE modeling to probe into the concrete effects of lockdown on atmospheric quality. Simultaneously, confounding factors of meteorological conditions were considered. Accordingly, the results illustrated that NO2 in different countries exhibited reductions during this special period, with a spectrum from 15% to 45% on average. While for O₃, the influence of pandemic on this secondary air pollutant is tiny and negligible, among which there is a slight decrease in the rural sectors, but a significant increase in the urban areas. The increase in O₃ in the urban area may be due to changes in chemical titration. Generally, a large amount of NO emitted by motor vehicles in urban centers will react with hydroperoxyl radicals to form ozone in the sunlight. The ozone concentration in the urban center area will be lower than that in the surrounding parts. Therefore, reduced NOx level is probably implicated in the increase of O₃ concentrations. When there is a sharp reduction in NOx emissions in urban areas, an increase in O₃ can be seen (Menut et al., 2020).
opposite tendency in the city of Rio de Janeiro, Brazil. Through an in-depth underlying mechanism of this behavior, data from two automatic monitoring ground stations showed that the ratio of non-methane hydrocarbons (NMHC) to NOx increased by up to 37.3% during the lockdown period. The sudden increase in the NMHC/NOx ratio is due to the fact that the reduction in NOx is higher than the reduction in hydrocarbons in this realistic scenario. In addition, according to the air masses trajectory, the VOCs mixture enjoys prominent reactivity in the industrial field, which may also be an important factor in the increase of ozone. The authors emphasized that their conclusions and similar phenomena around the world indicate that due to traffic restrictions and economic loss, the concentration of major primary pollutants has declined in the short term. However, secondary pollutants are still a major concern, such as ozone, with great increases or remaining stable during the outbreak (Siciliano et al., 2020).

In São Paulo state, Brazil, Nakada and Urban analyzed the data from four air monitoring stations to assess the potential influence of COVID-19 on atmospheric chemistry. Collectively, when comparing four-week mean data during the partial lockdown with the five-year monthly average data of April (2015–2019), there are variations in CO, NO and NO2, with the reduction values of up to 64.8%, 77.3% and 54.3%, respectively. On the contrary, after the same comparison, the ozone content in the urban area has increased by more than 30% (Nakada and Urban, 2020). Based on these analyses and results, the authors concluded that the favorable climate conditions for the diffusion of pollutants before the pandemic are comparable to the conditions during the blockade, which can exclude the influence of the diffusion itself on the results and interpretation. Moreover, as a city in the southern hemisphere, whose location and meteorological parameters are literally different from those cities in Europe and Asia, in which similar research data were recorded and reported (Nakada and Urban, 2020). These outcomes provide evidence that the lockdown has affected air quality to a certain extent.

Collivignarelli and co-workers focused on the effects of lockdown on the variations of air quality in Milan, Italy. After collecting and processing the meteorological factors, such as humidity, temperature, and wind speed, as well as rainfall and solar irradiance, the authors concluded that there were different changes in several types of pollutants. During the containment period, pollutants such as PM10, PM2.5, and black carbon, with benzene, CO and NOx were reported to be significantly reduced mainly due to the restriction of vehicular activities and human mobility. Moreover, the reduction in SO2 was noticeable in Milan, but there were no apparent changes in adjacent areas. Oppositely, ozone was increased significantly when the average concentration in February and March from 2016 to 2018 was set as a reference level. The increase in ozone (O3) is probably attributed to the appreciable decrease in NOx concentration. Thereinto, a more pronounced O3 level was observed in Milan, which may be explained by the fact that the average level of benzene in Milan is higher than that in neighboring regions, which may play an important role in the formation and promotion of O3 (Collivignarelli et al., 2020).

Sharma and co-workers estimated the impact of restricted human activities on air quality in 22 cities in India. According to the results, among the six criteria pollutants detected, PM2.5 experienced the largest reduction. On the contrary, the O3 content increased in multiple areas, and the underlying reason can be explained by the decrease of PM2.5 and NOx. Thereinto, O3 was the most dominant pollutant in four cities. This provides a lesson for us, that is, apart from the primary emissions, attention should also be paid to secondary pollutants. It is of great importance to grasp the atmospheric process by which precursors form final products, which is essential to control secondary pollutants and achieve beneficial results (Sharma et al., 2020).

The unprecedented restriction in social activities amid COVID-19 provides an excellent opportunity for us to understand the changes in atmospheric chemistry under the conditions of reduced urban major emissions. Through these studies, focusing on how the primary pollutants can be effectively reduced is not adequate, because primary pollutants have experienced drastic diminution but O3 is still increasing (Sicard et al., 2020). What is more, considering the important role of meteorological parameters in the spread of coronavirus and variations of atmospheric chemistry, future efforts are still required to achieve more convincing data and explanations.

3. Impacts of COVID-19 on ambient particulate matter (APM)

Ambient particulate matter (APM) is a mixture of solid particles and droplets present in the air. A portion of particles can be seen by naked eyes due to the large size and dark color, while other portions could only be detected under the special equipment. APM can be roughly divided into several subtypes according to their aerodynamic diameter, including coarse (PM10), fine (PM2.5) and ultra-or nano-fine (PM0.1) particles. Composed of different types of components, including chemicals and biological constituents, APM has been reported to induce multiple system damage, including the respiratory system, cardiovascular system, and central nervous system and immune system, as well as reproductive system (Alemayehu et al., 2020; Guan et al., 2020; Peoples, 2020; Wang et al., 2017; Wei and Tang, 2018; Yue et al., 2020; Zhao et al., 2020b). Furthermore, epidemiological studies have authenticated the association between APM and mortality (Chen et al., 2020a; Kim et al., 2020; Pope et al., 2020).

3.1. Fine particulate matter (PM2.5)

During the lockdown, it can be seen that the concentration of APM has been appreciably reduced. According to the information from Copernicus Atmospheric Monitoring Service (CAMS, 2020) of the European Union, relative to the mean value of the monthly averages for February from three consecutive years of 2017, 2018, and 2019, there was a visible decline in the monthly average of PM2.5 concentration in February 2020, by about 20–30% in most areas of China (Zambrano-Monserrate et al., 2020).

Wuhan is the epicenter of the COVID-19 outbreak in China where the first case was reported. An unprecedented stringent blockade measure was adopted in Wuhan from 23 January 2020 to curb the spread of coronavirus. Due to the extremely strict restriction followed, its population spent almost all time staying at home except for the purchase of daily necessities and other essential activities. As the central city of China in this special time, it is of utmost importance to investigate the changes in atmospheric chemistry in this area, which will help us understand the dynamic changes of air quality during special periods and give a reference for other similar megacities in other countries. Zheng and colleagues focused on this issue and aimed to examine the variations in chemical species and contributions of sources. By comparing the data between the lockdown period and the same days last year (January 23–February 22), it indicated that the PM2.5 level reduced from 72.9 μg/m3 last year to 45.9 μg/m3 this year, which is mostly resulted from decreased emissions. For its components, there are different extents of decline, with the lowest of 0.85 μg/m3 in chloride to the highest change of nitrate being 9.86 μg/m3. Based on the decreases in trace elements and elemental carbon, primary pollutants seem to be diminished, while increased levels in sulphate, organic carbon, and secondary aerosol indicated an increase in the formation of secondary particulate pollutants. Limited human activities such as firework burning and industrial production was the key reason for the changes in the component of PM2.5 (Zheng et al., 2020).

According to the report by Zambrano-Monserrate et al. (2020), reductions in NO2 by about 22.8 μg/m3 and PM2.5 by 1.4 μg/m3 were observed in Wuhan, China. Among the other 367 cities in China, the average decline of PM2.5 is even greater than that in Wuhan, China has an average of 18.9 μg/m3. Due to the stringent lockdown, at the huge costs of freedom of citizens, in particular populations in Wuhan, China has gained a remarkable achievement in pandemic control. According to the
statistical data from the Ministry of Ecology and Environment of China, and the graph shown in the recent study by Wang and Su (2020), six typical air pollutants except ozone have declined to varying degrees during the outbreak in China, indicative of a sign of gradual improvement of atmospheric quality during this quarantine period (Fig. 5). In relation to the first quarter last year, the average concentration of NO$_2$ in the first quarter was 24 $\mu$g/m$^3$ with a 25% of reduction this year, 2020, which is concluded from the data collected from 337 cities equal to or above prefecture-level (Wang and Su, 2020; MEEC, 2020).

Looking at other Asian countries and regions, in Dubai, an 11% reduction in PM2.5 was observed during March 2020 relative to March 2019. Meanwhile, a 6% drop was determined when compared to February 2020, which may be explained by the lockdown measures. Of note, the authors suggested that the lockdown deployed by Dubai included different phases, between which the intensity and effectiveness varies a lot, from the initial undemanding control to the least strict stage. Also, changes in PM2.5 levels are different between different stages (Chauhan and Singh, 2020).

For Delhi and Mumbai, two Indian cities, there were declines of 35% and 14% in PM2.5 concentration after lockdown with respect to the same period (March) in 2019, respectively. Similar to this phenomenon, the PM2.5 level dropped by half in March 2020 in Beijing, China, in comparison with the last month. During March 2020 in Shanghai, China, PM2.5 also dived by nearly 50% relative to the same period last year. The weakening of anthropogenic activities, combined with important meteorological factors could be used to well explain the obvious alleviation of atmospheric particulate matter in these areas (Chauhan and Singh, 2020).

In Malaysia, the positive impact of strict measures on air quality is reflected in the sharp drop in PM10, with a 28–39% of reduction in the industrial regions and 26–31% in the urban sites, respectively. For PM2.5, relative to the previous years (same periods in 2018 and 2019), it has been decreased by 20–42% in industrial sectors and 23–32% in urban areas, respectively (Kanniah et al., 2020). In a parallel study, Abdullah and coworkers used the special period of Movement Control Order(MCO) in Malaysia to investigate the effects of this control on PM2.5 changes. By tracking dynamic data from 68 monitoring stations, MCO has positive effects on air quality as almost all the detected areas showed reductions in the daily PM2.5 concentration when comparing the data before and during MCO. The highest decrease can be achieved up to 58.4%. But it is worth noting that the authors emphasized that this decline in PM2.5 is associated with the imposed measures, but it may also be linked to other important factors, especially weather conditions, which still needs further studies (Abdullah et al., 2020).

Recently, Chauhan and Singh made an analysis for the changes in PM2.5 in different cities before and after the lockdown, based on data from December 2019 to March 2020 (the period after the outbreak of COVID-19), and the records from the earlier years of 2017–2019 (before COVID-19). The result hinted that reducing social contact and staying at home can not only help curtail the spread of SARS-CoV-2 but achieve benefits in PM2.5 control as well. Specifically, In the U.S., partial lockdowns were announced in March 2020, during which a linear decline in PM2.5 was observed in New York and Los Angeles (Chauhan and Singh, 2020). It is still worth noting that since the PM2.5 level is closely related to local meteorological conditions, such as temperature, humidity and wind velocity, the significant changes in PM2.5 may not be simply attributed to lockdown implementation. For example, PM2.5 was reduced in March 2020 in New York, in which rainfall could also play a role. Therefore, when studying the important effects of lockdown on ambient air quality, meteorological parameters and synergistic effects should also be taken into consideration.

From December 2019 to March 2020, the average level of PM2.5 was around 29.38 $\mu$g/m$^3$ in Zaragoza, Spain. Compared to February 2020, there was a 58% decrease in PM2.5 concentration in March 2020. During the period from December 2019 to March 2020, the average level of PM2.5 was 35.0 $\mu$g/m$^3$ in Rome, Italy, where PM2.5 concentration in March 2020 was comparable to that in the same month last year, but it was significantly declined by 24% compared with February 2020, and by 159%, compared with January 2020, respectively (Chauhan and Singh, 2020).

3.2. Coarse particulate matter (PM10)

One such latest study that focuses on the impact of COVID-19 on the environment in Ghaziabad, India, employed three different phases to capture the pollutant variation, including pre-lockdown (10 January, 30 January and 19 February), partial social isolation (10 March), and after totally strict lockdown announced by the government (30 March and 19 April). By compiling the daily concentration of four classical pollutants, including PM2.5, PM10, NO$_2$ and SO$_2$ during these selected days, and meanwhile involving the data from the same dates last year, it is plausible to make a comparison in pollutant levels between (pre/amid/post-lockdown). Consequently, when compared with the pre-lockdown dates, these four types of pollutants plummeted in Ghaziabad after strict restrictions. Moreover, levels of these four pollutants on a certain day of 14 April 2020 (after strict lockdown) were employed to make a comparison with those levels on 14 January 2020 and 14 April 2019. Compared with 14 January 2020, the concentrations of PM2.5, PM10, NO$_2$ and SO$_2$ have reduced by percentages of 85.1, 50.8, 48.7 and 14.3, respectively. As compared to the same date in 2019, there are correspondingly 46.1, 40.2, 34.4 and 16.3% of reduction in PM2.5, PM10, NO$_2$ and SO$_2$, respectively (Lokhandwala and Gautam, 2020). Furthermore, daily average concentrations of the first week from four consecutive months of January-April 2020 were calculated and analyzed. Four months were employed, with January-March being set as a reference level and the fourth month being considered as lockdown condition. The detected pollutants included PM2.5, PM10, NO$_2$, NO, O$_3$, NH$_3$, CO and Benzene. After hypothesis proposal and statistical analysis, the authors pointed out that lockdown has no significant effect on SO$_2$ level, but represents statistical significance for other pollutants. The average level of PM2.5 has a strong correlation with other pollutants other than SO$_2$, and the same goes for PM10 (Lokhandwala and Gautam, 2020).

In India, aerosol optical depth (AOD) concentration has been drastically decreased (Fig. 7). In megacity Delhi, India, Mahato and colleagues collected and analyzed data about seven pollutants (PM10, PM2.5, SO$_2$, NO$_2$, CO, O$_3$, and NH$_3$) from 34 monitoring spots, and found that relative to the pre-lockdown period time (3 March to 24 March 2020), daily level of PM10 and PM2.5 enjoyed a maximum decrease of above 50% during restrictions. With regards to the same period last year, the lockdown has also witnessed reductions in PM10 and PM2.5 (24 h average) with magnitudes of 60% and 39% respectively. For other pollutants, NO$_2$ (24 h average) and CO (8 h average) levels dropped by 52.68% and 30.35% within the lockdown phase. From a whole perspective, air quality has been improved even after four days after the imposed lockdown in Delhi (Mahato et al., 2020).

The quarrying and crushing areas in eastern India are always heavily polluted. In a recent study, Mandal and Pal treated them as objective areas to explore the impacts of mandatory restrictions on environmental changes. The studied factors included PM10, land surface temperature (LST) and noise, and river water quality as well. The maximum PM10 level was dramatically reduced from the range from 189 to 278 $\mu$g/m$^3$ before lockdown to the current spectrum from 50 to 60 $\mu$g/m$^3$. This change can be observed only after 18 days of strict restriction. Relative to the pre-locking phase, LST dropped by 3–5 $^\circ$C, and the noise level decreased from above 85dBA to less than 65dBA during the lockdown period. Moreover, it seems that the water quality of the river has been improved with significant reductions in rubbish and household waste (Mandal and Pal, 2020).

In Africa, a study conducted in Salé City, Morocco, confirmed the phenomenon that reduced emissions and improved air quality have been achieved during the lockdown period. As a consequence of the restricted measures undertaken, automobile exhausts and industrial production...
emissions have been greatly reduced, which directly or indirectly results in a decrease in the daily average concentrations of PM10, NO$_2$ and SO$_2$ during this special period (March 21 to April 2) to different degrees as compared to the period before (March 11 to 20), with the decreased rate of 75%, 49% and 96%, respectively. However, these pollutants are always influenced by multiple factors. Only considering human activity is not enough to make an impartial judgment. For example, the benefits of local PM10 reduction could be counteracted or even surpassed by the invasion of aerosols outside the detected area through long-distance transportation (Otmani et al., 2020).

In most areas mentioned above, different extents of declines in APM have been observed after the commencement of stringent restrictions on transportation, commercial activities and unnecessary social contact. The group of people with chronic diseases who is susceptible to APM could get some temporary relieves amid lockdowns. The restrictions make people almost all stay at home and thus dampen the adverse effects of anthropogenic activities on the surrounding environment. Reduced traffic load and industrial activities are shedding light on the reduction in APM and natural rehabilitation. However, household emissions may be substantially increased because the time at home is getting longer.

4. Implications of COVID-19 in plastics pollution

4.1. Medical waste and disposed masks

As there are no effective clinical medicines to date, social distancing has been authenticated to be one of the most effective ways to control and prevent the spread of the virus (Courtemanche et al., 2020; Lewnard and Lo, 2020). Wearing a mask when necessary and cleaning hands with hand sanitizer regularly are effective measures to protect from infection, especially for those at high risk of exposure, including health workers, the elderly and people with pre-existing chronic diseases who have relatively weak immune systems and are more susceptible to virus (Feng et al., 2020; WHO, 2020b). A large number of medical staff are still working at the front line to combat the coronavirus. The daily substantial demand for medical materials and production of medical wastes put a lot of pressure on the natural environment. So far, in the absence of specific drugs and therapies, the most effective way to protect yourself is to wear a mask in a certain case, wash hands frequently and to maintain social distance. According to WHO estimates, the number of masks to be used every month during the pandemic is about 89 million (WHO, 2020c). It is conceivable that the demand for masks has increased dramatically in such a short period of time. During the outbreak, Wuhan hospitals generated an average of 240 metric tons of medical wastes per day, much higher than the previous average of fewer than 50 tons. In other countries, medical waste is also increasing. In the U.S., waste generated by personal protective equipment (such as masks and gloves) has also increased (The Verge, 2020; Zambrano-Monserrate et al., 2020). One of the foreseeable consequences is the tremendous pressure to manage and dispose of accumulated waste.

Masks are usually used to protect us from droplets shed from the respiratory systems from virus-carrying people passing by in the proximity of you, especially from those suspected infectors and patients. The droplets in the outer layer of the masks contain a certain amount of virus. Therefore, improper disposal in the environment would probably enhance the risk of secondary infection for cleaners and sanitation workers who pick up garbage to keep our community clean. According to OceansAsia, as shown in Fig. 8, a portion of single-used masks was not properly discarded in different scenarios. These single-used masks appeared in landfills, oceans, drainages and grasslands. All these pieces of evidence support that the global COVID-19 pandemic has led to increased risks of plastic pollution, which has brought pressure and challenges to our environment. It is necessary to appropriately manage discarded masks after the pandemic, which

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**Fig. 7.** A. NO$_2$ emission before and after a lockdown in India. Satellite images of NO$_2$ levels in Indian atmosphere (ESA, 2020d). B. Aerosol optical depth (AOD) concentration in India from the period March 31 to April 5 in 2016–2020 (NASA, 2020d).
Fig. 8. Collection of various COVID-19 face masks of different types and colors from ocean and terrestrial environment. One of many surgical masks washed up on the beach at the Soko Islands. Some of the many mask found on the beach washed up during the corona virus. Photo credit: OceansAsia.

requires reasonable methods and policies to avoid global plastic pollution (Fadare and Okoffo, 2020).

4.2. Food take-away and plastic pollutants

A recent study conducted by Fadare and Okoffo raised a concern that microplastic fibers in masks as a new environmental challenge pose a threat to the environment and humans (Fadare and Okoffo, 2020). They analyzed the main constituents of the used masks. High content of polypropylene was detected in the outer layer of the mask, and the inner layer contained high-density polyethylene. Polymer materials have been identified as important sources of plastic pollutants in aquatic and terrestrial media. These results provide evidence that improper disposal of used masks would lead to particulate contamination (Fadare and Okoffo, 2020).

When used masks are discarded at will and enter the environment, under special environmental conditions, micro/nano plastic fibers may be emitted into the terrestrial area, thereby affecting the growth of land species and crops. Similarly, plastics and other components could also be discharged into waterways and finally reach rivers, oceans and other aquatic areas where marine communities would be adversely influenced (TM. Adyel, 2020). Once masks reach the ocean, these wastes may be mistaken for food and eaten by marine species. Furthermore, soil deposition and marine accumulation would adversely affect crops and fish which are the main food sources for humans. Once they are heavily contaminated, global food safety will be raised as a thorny issue again.

On the one hand, disposable masks help us prevent the spread and infection of SARS-CoV-2, thereby sustaining public health. On the other hand, the sharp increase in the consumption of masks has led to a possible increase in microplastic pollutants released into the environment, which will cause environmental problems on the way. The scientific community, relevant authorities and the public should be aware of this potential damage.

Owing to restrictions and social distance, the restaurant industry has experienced an unprecedented recession in many countries. People were not allowed to dine in but could take away and enjoyed food delivery. In this case, the demand for packaging and plastic materials has risen sharply. Meanwhile, beverage bottles, food packaging bags and fast food containers in domestic waste have surged. The quarantine/isolation measures under this special situation directly led to an increase in the demand for online shopping and takeaway services. Most consumption patterns in physical stores have shifted to home delivery. In this case, the production of organic and inorganic waste has increased dramatically, which will lead to plastic pollution (Tanveer, 2020; Zambrano-Monserrate et al., 2020).

Polystyrene and other analogous chemicals are raw materials for packaging and container production, which can be released into the ecosystem, spanning from soil deposition to ocean accumulation (Ferreira et al., 2019; Ng et al., 2018; Shen et al., 2019; Wu et al., 2020a). It has been widely reported that micro/nanoplastics have adverse effects on marine organisms, and human beings (Haegerbaeumer et al., 2019; Kögel et al., 2020; Revel et al., 2018; Smith et al., 2018). In the long run, raw materials for packaging are also the main source of micro/nanoplastics pollutants in the environment, which will give rise to excessive plastic waste disposal. Apart from plastics materials, there are also complex organic components that are difficult to biochemically degrade. These risk factors will collectively or synergistically cause adverse biological effects on different species, and ultimately affect public health through the food chain and bioaccumulation.

During this period, the existence of these difficult problems highlighted the importance of understanding and problem-solving capabilities. The relevant authorities need to mobilize the public to raise awareness of the necessity of environmental protection and self-preservation. At the same time, it is essential to develop environmentally-friendly substitutes (biodegradable) in the production of containers and packaging, which can assist in effective decomposition and degradation of materials under natural conditions, thereby helping us protect the environment and achieve sustainable development (Fadare and Okoffo, 2020).

5. Post-pandemic symptoms and psychological trauma

The COVID-19 outbreak has claimed a huge number of lives and put tremendous pressure on the healthcare system. To suppress the transmission of this virus, a series of blockade campaigns have been launched, including traffic restrictions, social isolation, and extensive closure of industrial and recreational facilities. By strictly adopting these measures, the spread of the coronavirus in some regions has been effectively controlled. The eminent effects in Wuhan have been observed where the virus has been curtailed, with several hundred to several thousand increases each day in the beginning to the zero increase in confirmed cases currently (Lau et al., 2020). Staying at home, people have more time to focus on themselves, reflect on themselves, and reconsider the harmonious relationship between man and nature. It provides a great opportunity to reflect on us and the things around us and to better understand the importance of the earth in such an exactly tough period. In adversity, people are learning to self-inspection and to respect all lives that deserve the same natural resources as we humans.

However, with these restrictions, the global economic circle has been overwhelmed. So many industrials and fields are at a standstill, and a vast number of people are unemployed. The blocked industries and activities of retailers, closure of airlines and movie theaters have caused a lot of employees to lose their jobs, and fundamentally changed their way of life. Additionally, due to the suppression of social interaction between friends, colleagues and neighbors, people can only stay at home and work remotely. In this regard, some adverse consequences have progressively emerged. For example, the majority of people are only allowed at home without any job or entertainment, which will make them alienated from society. Aesthetic values and recreational activities are essential for maintaining human social and psychological stability.
Isolation from social interactions, and a shortage of wholesome entertainment, together with huge pressure from extensive job losses, a portion of residents are at greater risk of psychological trauma.

Unfortunately, coronavirus-positive patients may have gone through a dark period before being cured. ARDS and other sequelae probably significantly. During COVID-19, it has witnessed effective mitigation in APM and APM may be relatively afflicted with psychological adverse events further, such as post-traumatic stress disorder (PTSD), depression, and anxiety(Asmundson and Taylor, 2020; Huang and Zhao, 2020; Moghanibaishi-Mansourie, 2020; Roy et al., 2020; Shanafelt et al., 2020; Sher, 2020). This may last longer and affect the entire life of these recovered people.

6. Discussion and perspectives

While COVID-19 has given a punch to the global economy, leading to rising unemployment and social turbulence in some western countries, a blessing in disguise shows that the air quality has improved significantly. During COVID-19, it has witnessed effective mitigation in APM levels and GHGs. In most countries, atmospheric pollutants have been greatly reduced during this special period, including NO₂, CO₂ and APM. As of July 2020, many countries are relaxing blockade to revive their economy and recover social order. With the relaxation of restrictions in certain regions and countries, people’s daily lives are returning to normal, and industries are resuming activities and production. It can be deduced that energy demand and waste emissions will be on the rise, which probably exceeds the level before the COVID-19 outbreak. Therefore, the air quality is likely to return to the state before the lockdown, and even the beneficial effects of improving air quality during the pandemic will soon be offset. Furthermore, since the spread of the virus is related to temperature, humidity and other meteorological parameters(Auler et al., 2020; Goswami et al., 2020; Holtmann et al., 2020; Li et al., 2020a; Ma et al., 2020; Shi et al., 2020; Tobias and Molina, 2020; Wu et al., 2020b), it may cause a second wave of infections in most parts of the northern hemisphere in the coming winter.

Substantial efforts have been poured into controlling the spread of the SARS-CoV-2 at the huge price of economic recession and shrinking labor market. It seems that social isolation is given credit for the improvement of environmental conditions. However, it is still questionable how long the drop in emissions and pollutants could persist. The promising environmental benefits and recovery may prove to be transient. Besides, long-term implications would mainly rely on the duration of pandemic(Gillingham et al., 2020). As a lesson learned, the improvement of air quality is an optimistic consequence, but what needs to notice is the bounce-back effect, and the urgently tough problem to be tackled is how rebound effects can be lessened to a maximum extent. The authorities concerned should consider the adverse effects of economic recession, and deeply think about whether these observable silver linings could offset the long-run predictive/realistic detrimental effects on its populations. Carefully and actively listen to the opinions of scientists and related experts, and make decisions or policy on the basis of local and national dynamic conditions to minimize deterioration as much as possible in the foreseeable future. Some suggestive recommendations and strategies to better guarantee environmental sustainability may include:

6.1. Regular blockades in certain areas help self-healing and make a cleaner environment

Apart from atmospheric changes, reducing noise helps the world restore peace and tranquility. Constructional and cultural noise has been dramatically reduced which seems to go a long way in maintaining physical and mental health (Lercher et al., 2002; Stansfeld et al., 2000). The waters have become clearer and more transparent than before. The situation caused by the COVID-19 pandemic provides opportunities for natural self-purification. Based on the information mentioned above, this pandemic indicates that the rising pollutants and natural destruction due to human activities are not completely irreversible, and cast the light on air pollution control through a new method. An impaired environment can be efficiently restored only if strategies and responsible behaviors are reasonably adopted. Therefore, in the post-COVID-19 period, it is advisable to carry out regular blockades in certain areas, such as tourism scenic areas and overexploited natural areas, to assist in natural auto-regeneration. Furthermore, a series of methods should be considered for long-term amelioration of ambient pollutants, such as appropriate control of industrial emissions, strictly implementing traffic control, as well as introducing the odd-and-even license plate scheme(Chiaramonti and Maniatis, 2020).

From this pandemic, a good implication is that the reduction of human activities facilitates natural self-rehabilitation, and improves air quality. Appropriate strategies were developed to combat COVID-19 in different countries. Effective restrictions in the movement of citizens or travelers at the local and national levels represent observable benefits in terms of ecosystem restoration (National Geographic, 2020). At the same time, people are locked at home that may directly lessen human interference to nature, which provides unprecedented freedom for wildlife and allows them to enjoy life leisurely. The free movement of wild animals can be spotted in areas dominated by humans every now and then in some remote urban areas. Through this pandemic and observed phenomena, we can know that anthropogenic activities are the main reason for environmental degradation and ecological disturbance. Within such a short period, air quality has been improved, which suggests that regularly locking the landscape is instrumental for environment self-healing and self-cleansing.

6.2. Update energy infrastructure and explore biodegradable substitutes for plastics usage

Also, it is indispensable to update energy infrastructure and to develop renewable technology and environment-friendly power sources, which may solve the problems of the post-epidemic era in the long run, otherwise detrimental emissions and exhausts would skyrocket soon. Sustainable fuels and biodegradable packaging materials should be designed and incentivized. To achieve this, biofuels and bioplastics should be safe-by-design with safer consumption and production. And simultaneously, the pursuit of environmental friendliness is also of utmost importance that can be somewhat achieved by free of harmful chemicals or/and additives.

Plastic does provide a wide range of characteristics and performance, which greatly improves our quality of life, so it is difficult to imagine life without plastic. We must seek sustainable resources to promote the sustainable development of the environment. Biodegradable plastics may be a solution in the early stage, but in the long run, expanding the scale of innovation for more suitable candidates with environmental friendliness is necessary to ensure a better ecosystem. Such the application of clean technology and effective plastic waste management system should be implemented in the next coming years. With the innovation of technology and changes in lifestyle, policies should emphatically prioritize prevention and the overall reduction of plastics (Patrício Silva et al., 2021).

Furthermore, stringent laws and regulations should be conferred to the process of production, consumption and management of plastic products. Meanwhile, exploring effective methods for disposal and reuse of plastic waste, and encouraging redesign and recycling plastics pollutants are extremely crucial. Before the reform and upgradation of plastics, the top priority currently is to strengthen the monitoring of plastic waste on water, landfill and terrestrial areas after the global pandemic(Patrício Silva et al., 2021). In addition, environmental
behavior, transformation and bioaccumulation of plastic pollutants should also be considered for further research.

6.3. Establish synergisms between the general public and government to increase responsibility

The mitigation of environmental pollutants seems to help promote public health. It is estimated that within two months of the outbreak, NO₂ air pollution has been dramatically reduced in China. According to reports, in a hypothetical scenario, this reduction is expected to help avoid 6% of mortality caused by air pollution, which is equivalent to approximately 100,000 saving lives in China alone. The number of saved lives due to improvements in air quality have outnumbered the death tolls attributed to this pandemic in China (Chen et al., 2020b; Zambrano-Monserrate et al., 2020). On the contrary, in the U.S., the confirmed cases and deaths are still progressively increased up to now. Although several types of pollutants are also proven to be reduced to varying degrees in the U.S., which assisted in saving around 200 lives per month, it is just a small consolation confronted to the whole number of deaths caused by COVID-19 (Gillingham et al., 2020).

The fundamental reason for this difference between the two countries in the number of deaths and confirmed patients can be mainly attributed to the different attitudes towards this virus and the distinct steps taken by governments and citizens. In China, due to the threats of COVID-19, the Chinese government carried out unprecedented social lockdowns. On 23, January 2020, Wuhan city as the epicenter of COVID-19, initiated social control campaigns, where train stations and airport checkpoints block people from leaving and entering this city. Subsequently, the social distance and other measures were soon taken in whole of China. With the stringent implementation of these restrictions, the population in Wuhan were isolated from other parts of China. It exactly helped the nation quickly and effectively control the spread of SARS-CoV-2. Between adjacent villages and residence communities, paths and entrances have been gated off with stone piles, vehicles and tree trunks and other improvised barriers (The New York Times, 2020).

As the most populous country globally, it is not easy for China to make such impressive achievements, which are closely related to the correct leadership of the government and the cooperation of populations. WHO praised China for “China has rolled out perhaps the most ambitious, agile and aggressive disease containment effort in history” (WHO, 2020), and appreciated the contribution of China to global SARS-CoV-2 control. In the U.S., although it enjoys advanced healthcare systems, control campaigns have been failed, and the number of infection cases dramatically surged. The potential reason for the fundamental difference between China and the U.S. could be explained by the fact that the Chinese government has the absolute right to confer measures and the public will unconditionally abide by the announced orders. While in the U.S., a large group of people pursued freedom who did not implicitly comply with preventive measures. Combined with lots of political issues and limitations, COVID-19 has taken a vast number of lives in the U.S.

6.4. Improvement of social awareness

One of the harmful effects of COVID-19 is the accumulation of large amounts of clinical waste and plastic contaminants in such a short time, due to the increasing consumption of medical products. The outbreak of the coronavirus has increased medical demand and healthcare services, among which a large quantity of medical waste is regularly generated every day. In this dark period, the frequency of use of masks has greatly increased, which will enhance the burden of management and waste disposal of personal prevention equipment, such as used masks, disposable rubber gloves and bottles of hand sanitizer on a routine basis. In different processes, the ingredients and wastes themselves can be directly released into the environment, which will cause environmental pollution and habitat destruction. Moreover, discarded used masks carry numerous unknown pathogens and can persist in the environment for a long time. Masks and other medical wastes, as the medium for the propagation of micro/nanoplastics, are potential sources of pollution and hotbeds of virus transmission. These obvious adverse effects remind us that the situation is still severe. It is critical to make the safe management of medical waste during and after emergencies. These used masks should be treated as hazardous materials separately. The dramatic rise in the consumption of masks has identified the need to raise public awareness for the hazards of disposable masks that are discarded casually. Necessary measures should be taken to popularize the potential adverse effects of the plastic pollutants and make the public accountable for their behaviors and actions.

Raising awareness over plastic waste and contamination should not be interrupted nor reversed, as it required long-term efforts to result in behavioral changes. When decision-makers strive to raise environmental awareness in the general public and persuade people to change their lifestyles on consumption patterns and behaviors, it is advisable to develop effective communication strategies and combine the strength and credibility of the scientific community to the realistic communication, research and solutions. In addition, communication forums should be stimulated through public participatory approaches to help operate and disseminate knowledge, such as the adverse effects of plastic waste and pollution, which will play a positive role in changing behaviors in the general public even if it takes a long time.

6.5. Build a comprehensive framework for post-pandemic era

Understanding the association between COVID-19 pandemic and atmospheric variations helps design ideal strategies (virus-pollutant-health) for further virus and pollutants control and public health prevention, especially during similar tough periods. COVID-19 crisis exerts both positive and negative impacts on the environment. The improvement of air quality is beneficial to the entire population of the world, especially for those with existing chronic diseases. Taking into account the drastic amelioration in air pollution after the quarantine (CO₂ emissions in China have been reduced by a quarter), it has helped to drastically reduce the number of deaths. The surprising prediction is that the number of saving lives presumably by the improved air quality in China seems to far exceed the number of deaths caused by a coronavirus (CNN, 2020b; Marshall Burke, 2020; Forbes, 2020a, 2020b). However, what is noteworthy is that the prediction model did not include the life loss attributed to economic burden, insufficient healthcare and other important factors. Therefore, for the total number of deaths during this period, it is still not clear whether saving lives by improved air quality can counteract the loss of life caused by other factors in the pandemic.

In addition, there is no doubt that COVID-19 has brought a terrible scourge to humankind, medical services, and mental health on a global scale. Confirmed cases or people with similar experiences, such as those recovering from SARS and MERS, may suffer from psychological trauma further. For ordinary people, their schedules on a routine basis have been disturbed for up to several months. During this quarantine time, people have more time to reflect on themselves and reconsider the relationship between humankind and the mother earth. The COVID-19 outbreak raises a cluster of tough questions. People are re-thinking the impact of our daily life on environmental sustainability (Fig. 9).

Environmental problems may last longer and surpass the produced benefits if countries neglect these adverse aspects, which will finally lead to much severer consequences and make conditions more challenging (Zambrano-Monserrate et al., 2020). Economic situations, atmospheric chemistry and human life may be all changed after the lockdown (post-COVID-19 era). These signs motivate and urge the human community to take timely and necessary steps to avoid further threats, and meanwhile rescue the damaged situations. After all, in the long run, whether it is a real benefit or temporary blessings largely dependent on how long the pandemic will last and what the policies would be conferred by the governments. From this lesson, it is necessary
to develop a buffer zone to help back to normal life, and to establish a comprehensive system to prevent future similar events, within which the pathogens, environmental sustainability and public health should be taken into account.

COVID-19 can be seen as a new opportunity and challenge for global solidarity to re-examine and re-understand the relationship between man and nature. The ultimate direction literally relies on public consciousness and governmental responses from different nations and cultural backgrounds to our already destructive environment. Politicians should pay more attention to the essence of the pandemic itself, and formulate timely and appropriate policies based on the recommendations from expert researchers, which would sustainably assist in public health, environmental restoration and economic recovery. It is time for us to defeat the virus and return to normal life together. As long as solidarity and cooperation are firmly formed at the national and international levels, it is possible to renovate the damaged nature from now in time.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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