Effects of the COVID-19 pandemic on the environment, waste management, and energy sectors: A deeper look into the long-term impacts

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Abstract

The COVID-19 pandemic has not only caused a global health crisis but also has significant environmental consequences. Although many studies are confirming the short-term improvements in air quality in several countries across the world, the long-term negative consequences outweigh all the claimed positive impacts. As a result, this review highlights the positive and the long-term negative environmental effects of the COVID-19 pandemic by evaluating the scientific literature. Remarkable reduction in the levels of CO (3−65%), NO_2 (17−83%), NOx (24−47%), $PM_{2.5}$ (22−78%), PM_{10} (23−80%), and VOCs (25−57%) was observed during the lockdown across the world. However, according to this review, the pandemic put enormous strain on the present waste collection and treatment system, resulting in ineffective waste management practices, damaging the environment. The extensive usage of face masks increased the release of microplastics/nanoplastics (183 to 1247 particles/piece) and organic pollutants in land and water bodies. Further, the significant usages of antibacterial hand-sanitizers, disinfectants, and pharmaceuticals, have increased the accumulation of various toxic emerging contaminants (e.g., triclocarban, triclosan, bisphenol-A, hydroxychloroquine, etc.) in the treated sludge/biosolids and discharged wastewater effluent, posing great threats to the ecosystems. This review also suggests strategies to create long-term environmental advantages. Thermochemical conversions of solid wastes including medical wastes and for treated wastewater sludge/biosolids offer several advantages through recovering the resources and energy, and stabilizing/destructing the toxins/contaminants and microplastics in the precursors.

Keywords: COVID-19; Air quality; Face masks; Emerging contaminants; Solid wastes; Pyrolysis; Hydroxychloroquine/chloroquine

Introduction

COVID-19 has spread over the world, causing a global health emergency. It was first reported in Wuhan, China, in December 2019 and soon spread throughout the country, becoming a global disease (Ali and Alharbi 2020; Zambrano-Monserrate et al. 2020). Coronavirus may have been transmitted from bats to people, according to one hypothesis (Brennecke et al. 2020). Humans were infected mostly by droplets, interactions, and airborne transmissions. COVID-19 has made a great impact all across the world. Almost all countries are currently focusing their efforts to prevent the spread of COVID-19 disease by enacting policies such as the complete closure of public places (Liu et al. 2021; Muhammad et al. 2020; Naethe et al. 2020). Though these policies or regulations may have a significant impact on the economies of most countries, they have some negative or positive effects on the environment, such as a substantial drop in the greenhouse gas emissions that have not been seen since World War II, as many industries in the world halted production and vehicle usage drastically decreased. These variables resulted in a significant drop in nitrogen dioxide (NO_2) and particulate matter ($PM_{2.5}$, diameter smaller than 2.5 μm) concentrations all across the world (Cui et al. 2020; Muhammad et al. 2020; Liu et al. 2021).

To prevent the rise of coronavirus sickness, every country's government has established social distancing regulations and forced its inhabitants to remain in their homes. Noise pollution levels have decreased dramatically in most countries due to reduced public and private transportation and other business operations (Jairoun et al. 2021). A critical link exists between emergency control and the betterment of pristine beaches, air quality, and environmental noise depletion. Conversely, additional harmful indirect factors, like minimizing recycling, and the rise in effluents, threaten the pollution of land and water bodies even more, besides air (Zambrano-Monserrate et al. 2020).

For instance, the demand for conventional energy has decreased by approximately 30% in several regions, and there has been a decrease in power consumption ranging from 12 to 20% for most countries (Mousazadeh et al. 2021). Although the pandemic had some direct and short-term positive consequences, it has more severe negative effects on plastic production and solid waste management. Unfortunately, in many countries, the COVID-19 pandemic has wreaked havoc on municipal solid waste management (Knowlton 2019). Some states in the United States, for example, temporarily closed recycling centers, ceased curbside recycling collection, and stopped onboard recyclables pickups owing to fears about the virus's spread. Pesticides, detergents, soaps, single-use plastic, and other chemicals have surged dramatically in recent months, wreaking havoc on the ecosystem (Baldasano 2020). In the last few months, roads, buildings, and entire cities have been sanitized. The utilization of hand sanitizers has risen dramatically as well. Personal protective kits, gloves, and face masks have emerged as important safety precautions during the continuing epidemic (Neumeyer et al. 2020).

Hand sanitizers containing isopropanol and alcohol are becoming more popular worldwide as a means of mass disinfection. In almost every location where people live, disinfectants such as hypochlorous acids, sodium hypochlorite, and chlorine are utilized in large quantities (Kumar et al. 2020; Tripathi et al. 2020; Capoor and Parida 2021). In addition, the excessive usage of antibiotics, disinfectants, antibacterial hand sanitizers and soaps during the COVID-19 pandemic will raise the concentration of these pharmaceutical and personal care products and other emerging pollutants in the discharged wastewater effluent from wastewater treatment plants (WWTPs), posing great threats to the aquatic life and ecosystems (Neumeyer et al. 2020; Rugani and Caro 2020). The extraordinary use of pharmaceuticals (e.g., antibiotics, disinfectants) and personal care products (e.g., antibacterial soaps and hand-sanitizers) which contains triclocarban (antibacterial) and triclosan (fungicide) (Du et al. 2019; Patel et al. 2019; Brennecke et al. 2020), will noticeably increase their concentrations in the WWTPs influent and effluent. For the microorganisms and environment, sodium hypochlorite is extremely toxic. Endocrine disruption and various other neurological consequences are all linked to these substances. Both compounds are harmful to the environment since they are hard to break down and makeup 60% of all drugs identified in sewage sludge. The aquatic fauna is adversely affected by these chemical pollutants (Kumar et al. 2020; Rizou et al. 2020; Capoor and Parida 2021).

Several studies and reviews discussing the positive impacts of COVID-19 on the environment have been punished, while limited published studies are studying the long-term negative impacts of COVID-19 on the environment and waste management. The present review paper discusses the positive and long-term negative impacts of COVID-19 on the environment, waste management, and energy sectors. It is very important to evaluate the long-term negative impacts of COVID-19 on the environment for future strategies and regulations. Furthermore, the information presented in this review can be used to assess short and long-term options for mitigating future harmful effects.

Short-term positive impacts of COVID-19 on the environment

Many studies confirmed that air quality improved only during the lockdown period in various countries all over the world. Major reductions in the levels of NO_2, CO, NO_x, SO_2, VOCs, and $PM_{2.5}$ were reported, which is mainly due to the lockdown and closure of many industrial and commercial activities in different countries including the United States (Chen et al. 2020; Son et al. 2020), Canada (Adams, 2020), Mexico, Italy, Germany, China (Jia et al. 2020a,b; Wang et al. 2021a), India (Selvam et al. 2020; Yunus et al. 2020), Iraq (Hashim et al. 2021), Egypt (Mostafa et al. 2021), etc (Table S1, Supplementary material). The details regarding the impacts of COVID-19 on greenhouse gases emissions, VOCs, particulate matter, and air quality index are given in the following sections.

Greenhouse gases (GHGs) emissions

In the United States, the pollution levels in the COVID-19 phase from March 13 to April 21, and before the COVID duration, from January 8 to March 11 were recorded in 2020. Notable NO_2 reductions were detected in 2020 than from 2017 to 2019, where a 25.5% reduction, including absolute mitigation of 438 ppb was recorded (Berman and Ebisu 2020). Another study showed that the data obtained from 28 long-term air quality sites demonstrated varying reduction levels of CO and NO_2 in the initial lockdown period of March 15 to April 25, 2020, in the US, corresponding to a reference duration, before lockdown, including previous baselines instituted from 2017 to 2019. The approximate reduction levels of CO by 37% and NO_2 by 49% are notable in around 67% of the regions and principally proliferate with the regional population density (Chen et al. 2020). Declines of 49 and 38% in CO and NO_2 levels were found at base level analyses in California, throughout the lockdown from March 19 to May 7 than before the lockdown on January 26 to March 18 in 2020 (Figure 1). Similarly, in Ontario, Canada, NO_2 and NO_x exhibited their lowest levels for 22 of the 29 recorders. Distinctive readings varied from 1 ppb of NO_2 and 5 ppb of nitrogen oxides (NO_x), which was above average to 4.5 ppb of NO_2 and 7.1 ppb of NO_x, which was lower than average (Adams 2020).

In Düsseldorf, Germany, the continuous observations of NO_2 level variations corresponding to the reduction of city traffic because of the lockdown enforcement were performed using down-welling light including RoX automated field-spectrometer. A decision tree was established by primary constituents that were disintegrated from down-welling radiance spectra, which showed to be the highest durable methodology to obtain NO_2 readings. Improved differentiation of the NO_2 readings-scale was derived with a partial least square regression model, and down-welling radiance measurements can be used to observe NO_2 levels continuously (Naethe et al. 2020).

In Italy, a study was conducted to measure the carbon footprint (CF) related to energy reduction because of economic undertakings and locations throughout the lockdown in the nation, and to equate these environmental obstacles with the quantified CF for corresponding durations around March and April from 2015 to 2019. The study demonstrates that CF during lockdown reduced by approximately 20% more than the average computed CF before. This indicates that greenhouse gases or GHGs were regulated within approximately 5.6 and 10.6 Mt CO_2e. Further studies indicate an inclination that happens toward larger impact savings in the Northern provinces, which is approximately 230 kt CO_2e of GHGs regulated by provinces on average, than approximately 110 to 130 kt CO_2e in the Southern and Central provinces (Rugani and Caro 2020).

In Madrid and Barcelona, Spain, the magnitude of the air pollution decline was measured in March and April 2020, during the lockdown, which demonstrated readings of a notable reduction of approximately 75%. The NO_2 levels in these two cities recorded a 50 and 62% reduction for Barcelona and Madrid, respectively. In March 2020, the hourly quantification readings were derived from 9 and 24 air quality sites from the recording systems, which provided data of the regulations, that can be accomplished by imposing low emission zones (LEZ), including the pollution level to be eradicated, which was 55% for Barcelona and Madrid (Baldasano 2020). Average monthly concentrations of pollutants in Tunisia examined from January 1 to April 30, 2020, revealed that actions taken to reduce the spread of the virus have a major impact on emission levels. In March, there have been 51% decreases for NO_2 and 52% for SO_2 emissions for most of the cities compared to January, while the levels of NO_2 and SO_2 decreased by about 40% (Chekir and Ben Salem 2021).

To investigate the effect of the lockdown on air pollution in Egypt with a focus on Cairo and Governorates of Alexandria, the data for the lockdown period in 2020 were extracted and contrasted with the corresponding month for the specified baseline period (2015–2019). The absorbing aerosol index (AAI) was reduced by around 30%, NO_2 declined by 15 and 33% respectively in Cairo and Alexandria Governorates, while CO reduced by around 5% in both Governorates. Furthermore, during the epidemic, GHG emissions have been cut by at least 4%, while the amount of ozone in Cairo and Alexandria rose by around 2% (Mostafa et al. 2021). In the United Arab Emirates, core data reveal that the AOD, NO_2, and Surface Urban Heat Island Intensity (SUHII) levels decreased in the lockdown period by 3.7, 23.7, and 19.2% in comparison with the same time of 2019 correspondingly. This study has shown that measurements of chosen air contaminants and SUHII data from satellites correspond highly to actual data (Alqasemi et al. 2021).

In São Paulo, Brazil, the lockdown was enforced on March 24, 2020, to reduce COVID-19 cases. The Business as Usual or BAU days with homogeneous weather situations were incorporated to decrease the impact of meteorology on ambient levels. The largest average level or ± standard deviation, on BAU days, was recorded at Congonhas station at $125.8 \pm 27.4\ \mu g\ m^{-3}$, based 500 m from Congonhas airport; and the lowest value was recorded at Pico de Jaragua at $17.3 \pm 5.2\ \mu g\ m^{-3}$ in the city suburbs. The highest absolute reduction in NO_x levels was observed at Congonhas at $-79.6\ \mu g\ m^{-3}$, succeeded by Marginal Tiete at $-59.2\ \mu g\ m^{-3}$ at the curbside of a notable-trafficked region. A significant decline was recorded for all sites with depreciation ranging from 34% at Osasco to 68% in Pinheiros. The traffic emission depletion led to air quality amelioration because it constitutes 67% of NO_x emissions (Krecl et al. 2020). Other studies in Brazil showed significant decreases in NO levels of 77.3%, CO of 64.8%, and NO_2 of 54.3%, were detected throughout the incomplete lockdown in urban regions than the five-year monthly average (Nakada and Urban 2020; Urban and Nakada, 2021).

In Central Eastern China (CEC), the angstrom exponent (AE) and the aerosol optical depth (AOD) in the lockdown from January 24 to February 29, 2020, rose and fell in many CEC places compared with the 21-year climatological mean from 2000 to 2020. In Wuhan and Hubei, the AOD or AE outputs reduced or rose by 31.0 to 45.3% and 39.2 to 29.4%, due to strict lockdown (Figure 1) (Shen et al. 2021a). The industrial activities, ongoing constructions, vehicle kilometers traveled, etc., fell tremendously in China, thereby causing less NO_x, and SO_2 levels by roughly 29 to 47%, and 16 to 26% throughout phase 1 and phase 2 response duration and ultimately enhanced the air quality during the national lockdown (Li et al. 2020). In Taiwan, the NO_2 column levels also fell by 24% in the third week of the Chinese New Year in 2020 than earlier (Griffith et al. 2020). In Shijiazhuang, China, nitrous acid (HONO) levels were quantified by implementing a recorder for aerosols and gases in ambient air or MARGA from December 15, 2019, to March 15, 2020, which included the Chinese New Year (CNY), the high air pollution period, and the COVID-19 lockdown phase. The air quality notably ameliorated due to the diffusion propensity proliferation of air clouds and the emission depletion in and post CNY, which incorporated the COVID-19 lockdown. The average HONO readings were 2.43 ± 1.08 ppbv before CNY; it abated to 1.53 ± 1.16 ppbv in the CNY and further mitigated to 0.97 ± 0.76 ppbv post CNY. Following the incorporation of the amelioration of the diffusion propensity, an approximate depletion of 31% of ambient HONO, 36% of $NO_{2,}$ and 62% of NO (Figure 1 and Table S1), were recorded in the lockdown phase, throughout and post CNY, then with those before CNY (Jia et al. 2020b). Another study was conducted to monitor NO_2 levels in 367 main cities in Northern China, which were separated into low, moderate, and extreme emission categories, as per their four-year mean NO_2 rating. NO_2 levels were determined every day for all emission categories, categorized the days as good, medium, and bad-meteorological conditions (Jia et al. 2020).

The measurement of NO_2, HCHO, SO_2, and CO levels, including the Aerosol Optical Depth (AOD) over Tokyo, Seoul, Wuhan, and Beijing-Tianjin-Hebei (BTH) region was undertaken in February 2019 and February 2020. NO_2 recorded the highest critical reductions of approximately

19, 33, 83, and 54% in Tokyo, Seoul, Wuhan, and BTH, respectively. Wuhan experienced the highest reductions in contaminants, by roughly 62% in AOD, with a 4, 71, 11, and 83% fall in column densities of CO, SO_2, HCHO, and NO_2, respectively. SO_2 levels climbed in Tokyo and Seoul because of vehicles coming from contaminated upwind areas, whereas the formaldehyde, CO, and NO_2 levels declined. A large rise in surface ozone in East China from February 19 to February 2020 was due to remarkable falls in NO_2 levels, which is possibly due to lower O_3 and NO reaction, by high NO_x dips and low NO_x saturation (Ghahremanloo et al. 2021).

In Hat Yai, Thailand, The NO_2 levels abated by 33.7% (Figure 1), respectively in the initial three weeks of the lockdown period than the similar phase, before the lockdown period. The NO_2 tropospheric readings recorded over the ground site and regionally including the spatial mean over the urban regions of the city were obtained from Sentinel-5P, which corresponds with the depletion levels derived from the ground site (Stratoulias and Nuthammachot 2020).

Particulate matter and VOCs

Several studies across the world reported a major reduction in particulate matter (PM) and VOCs. $PM_{2.5}$ levels demonstrated a reduction in the COVID-19 phase in the United States (Berman and Ebisu 2020). In California, the variations in $PM_{2.5}$ levels, which were around 2.5 μm were quantified in the mitigation period, versus the baseline or pre-mitigation quantification phase, by implementing the difference-in-difference methodology, and the approximate avoided overall and cause-specific fatality, due to $PM_{2.5}$ variations by district or state in the urban regions of 10 US states and the District of Columbia. The $PM_{2.5}$ levels declined in seven states, including the capital, in the abatement phase. The mean $PM_{2.5}$ level depreciation was approximately 0.25 $\mu g\ m^{-3}$ or 4.3% in Maryland to 4.20 $\mu g\ m^{-3}$ or 45.1% in California. $PM_{2.5}$ levels mitigated by 12.8% on average, in the capital, including the seven states. An approximate 483 or 95% CI: 307,665 fatalities, corresponding to $PM_{2.5}$ levels, were avoided in the urban region of California (Son et al. 2020). A decline of 31% in $PM_{2.5}$ level was found in California throughout the lockdown from March 19 to May 7 than before the lockdown on January 26 to March 18 in 2020 (Liu et al. 2021). Similarly, the PM_{10} and $PM_{2.5}$ levels notably reduced in the Northeast cities of California and Nevada (Chen et al. 2020).

In India, the analysis of the air pollutants falls throughout the lockdown of March 24, 2020, and April 20, 2020, was done by differentiating against the pre-lockdown phase of January 1, 2020, and March 23, 2020. The Central Pollution Control Board or CPCB reported lower air pollution throughout the lockdown with significant falls in air pollution in zone 2 comprising Gandhinagar and Ahmedabad and zone 3 of Rajkot and Jamnagar and slight fall in zone 1 comprising Vadodra, Surat, and Ankleshwar and zone 4 including Palanpur and Bhuj in the industrialized state of Gujarat. The concentration of $PM_{2.5}$ and PM_{10}, plummeted in the range of 38 to 78% and 32 to 80%, respectively (Selvam et al. 2020). In Ghaziabad, the lockdown led also to a substantial amelioration in environmental variables like air quality. The $PM_{2.5}$ and PM_{10} levels demonstrated reductions of approximately 85.1 and 50.8%, respectively in the city than on January 14, 2020, before the lockdown (Lokhandwala and Gautam 2020).

A separate spatial dispersion of the surface $PM_{2.5}$ was observed over Central Eastern China (CEC) throughout the lockdown, including increased levels in East and North China. Comparatively, high $PM_{2.5}$ levels were observed in the low flatlands of Hubei, where six distinct occasions of $PM_{2.5}$ contamination were discovered. Half of the occurrences of contamination were linked to long-range transport (LRT) of air contaminants from upstream areas of CEC (Shen et al. 2021a). Similarly, the bad-meteorological conditions experienced a 56% greater $PM_{2.5}$ level in extreme emission cities than low emission cities. Concerning the good meteorological conditions, the extreme emission category rose to 8.8 $\mu g\ m^{-3}$ in regular mean $PM_{2.5}$, from 2017 to 2019, including a 2.6% rise in the likelihood of extreme $PM_{2.5}$. But, the extreme emission, bad meteorological category witnessed a 24% dip in standard mean $PM_{2.5}$ levels from 2017, an extreme emission year compared to 2019, which was a low emission year (Jia et al. 2020a). Taiwan avoided an excess $PM_{2.5}$ of 19.2 μg m^{-3}, on average, throughout the event, similar to a 0.5 μg m^{-3} fall for the entire three-month winter season (Griffith et al. 2020). Similarly, a decrease in industrial activities, ongoing constructions, vehicle kilometers traveled, etc., caused reduced emission levels of VOCs, and $PM_{2.5}$ levels by roughly 37 to 57%, and 27 to 46% throughout phase 1 and phase 2 response duration and ultimately enhanced the air quality during the national lockdown (Li et al. 2020).

The air contaminants readings of $PM_{2.5}$ and VOCs in the non-regulatory phase or NCP from 24 December 2019 to 23 January 2020, and the control phase or CP from 24 January to 23 February 2020 were examined at Pudong Supersite or PD and the Dianshan Lake Supersite or DSL. The prevalence of fog or haze-like incidents, VOCs, and $PM_{2.5}$ levels fell significantly from NCP to CP and the mean percentages were 35.1, 38.9, and 31.6% at PD, and 37.9, 50.7, and 34.5% at DSL. The emission regulation of major sources like vehicle fumes and coal combustion caused low forerunner readings of NO_x and SO_2, which resulted in the decline of $PM_{2.5}$ from NCP to CP. The inadequate nitrogen monoxide titration, low relative humidity, and greater visibility than NCP may have caused extreme ozone levels at DSL and PD in CP. The VOCs also fell by controlled vehicular fumes and fugitive emissions, and the regulation of locally circulating air pollutants led to fog level dips (Jia et al. 2020b; Hashim et al. 2021).

The hourly $PM_{2.5}$ levels of related elements were quantified at a rural area between Beijing and Tianjin, China, before 12 to 25 January 2020; from 26 January to 9 February 2020, and post 22 March to 2 April 2020 in the control phase. Fe, Ca, K, Zn, Ba, and Cu were the primary elements, before the control period; and Zn smelter, vehicle emissions, and fireworks combustion constituted the largest proportions of the overall element mass of 12.1, 10.3, and 55%, respectively. K, Fe, Ba, Cu, and Zn were the principal elements in the control period; and vehicle emissions and fireworks combustion constituted 27 and 55% of the overall element mass. Fe, K, Ca, Zn, and Ba were the primary elements, post lockdown; and steel, dust, and the iron sector constituted 21 and 56% of the overall element mass (Cui et al. 2020).

Air quality index and O_3

The Ontario region in Canada announced a State of Emergency (SOE) in March 2020 to restrict the COVID-19 cases. A five-week phase in the SOE period was analyzed against an earlier five-week duration as a benchmark. Ozone concentrations at 12 of the 32 recorders were less than the preceding five-year phase. The mean ozone levels were 1 ppb less in the SOE phase. However, it varied from 1.5 ppb up to 4.2 ppb, which was lower than the long-lasting circumstances (Adams 2020). Conversely, increase in ozone levels was found in Rio de Janeiro, Brazil, due to the rise in NMHC/NO_x throughout social distancing, enforced due to the atmospheric chemistry in Rio de Janerio, regulated within VOC-monitored circumstances. The proportions of non-methane hydrocarbons and nitrogen oxides or NMHC/NO_x increased around 37.3% throughout the incomplete lockdown, according to the surveying data derived from two automated surveying sites. However, the rise was substantial when air clouds appeared from industrial regions, due to the large rise in VOC reactivity from the clouds, which are high in aromatic compounds (Siciliano et al. 2020). Similarly, an approximate rise of 30% in ozone was noticed in urban regions, largely determined by automobile traffic, possibly associated with nitrogen monoxide reduction (Nakada and Urban 2020; Urban and Nakada, 2021).

The effect of COVID-19 regulations was also investigated in Europe from 15 March to 30 April 2020, according to maximal regular 8-h running average ozone or MDA8 O_3 from European

Environment Agency's air quality database. The MDA8 O_3 levels were reduced in Iberia because of high specific humidity and low solar radiation, while ozone escalated in different regions. Northwestern to Central European area showed a notable rise in O_3 levels of 10 to 22% in urban background sites. The measurements of the approximate O_3 demonstrated that declined due to emission reductions, and O_3 variations were determined by meteorology (Ordóñez et al. 2020). In India, power plant operations probably caused a minimal fall in CO by 3 to 55% and the reduced discharge of NO enhanced the O_3 levels by 16 to 48% (Figure 1). AQI recovery of 58%, in general, was reported for the initial four months of 2020 than in 2019 (Selvam et al. 2020).

Freshwater quality

There is a noteworthy correlation between emergency procedures, enhancement of air quality, pristine beaches, and environmental sound depletion. Freshwater quality for some lakes was also improved regarding the suspended particulate matter or SPM in certain countries, including India, and the SPM output decreased up to 34% than the earlier years before the lockdown (Yunus et al. 2020). Figure 2 shows the tracking of the spread of SARS-CoV-2 in near real-time with a map-centric dashboard developed by Johns Hopkins University's Center for Systems Science and Engineering dashboard leading the pack (Johns Hopkins 2021). In Vembanad Lake of Southern India, which is the longest freshwater lake in India, the surface water quality recovered regarding the suspended particulate matter or SPM. SPM dropped by 15.9% on average from 10.3% to 36.4%, which is up to an 8 mg/l decline than the pre-lockdown phase (Figure 3). The computed SPM for April 2020 is the least for 11 of the 20 Vembanad lake zones. The SPM output decreased up to 34% than the earlier years from the preceding minima (Yunus et al. 2020). Conversely, there are adverse indirect characteristics like decrease in recycling and rise in waste, that jeopardizes the water and land pollution, including air, in the highly affected nations like Spain, Italy, USA, and

China, when analyzing the adverse and productive secondary outcomes of COVID-19 (Zambrano-Monserrate et al. 2020).

In summary, mostly all studies across the world confirmed remarkable improvements in air quality during the lockdown period because of the closure of several industrial and commercial activities which rely on fossil fuels, leading to a remarkable reduction in GHG emissions, particulate matter, and VOCs. Additionally, the global lockdown drastically affected energy resources as discussed in the section "Impacts on the energy sources", resulting in a remarkable decrease in energy usage and reduction in GHG emissions. The results clearly show that there is an urgent need to reduce the dependence on all fossil fuel-related energy sources, including oil, coal and natural gas, and increase dependence on other renewable resources to have positive long-term impacts on the global warming potential.

Long-term negative impacts of COVID-19 on the environment

Generation of biomedical waste and management issues

In several countries, the COVID-19 epidemic has resulted in not only health-related challenges such as job, mental illness, economic losses, socio-economic burdens, and waste management challenges (Le et al. 2020; Mofijur et al. 2021; Mousazadeh et al. 2021). It has put enormous strain on the present waste collection and treatment system, resulting in ineffective waste management practices like mobile incinerations and direct landfills for wipes, bottles of sanitizers, single-use masks, and gloves, which are crucial for the safety of frontline Corona pandemic workers. In the face of increasing panic, the single-use plastic manufacturing industry is attempting to seize the chance and resurrect an otherwise dwindling industry (Somani et al. 2020; Mousazadeh et al. 2021). Many supermarkets no longer allow consumers to bring reusable bags instead of delivering things in single-use plastic bags. There has been a rise in online shopping of meals in restaurants, resulting in a per capita rise in plastic usage, indicating that global plastic pollution has increased due to the COVID-19 pandemic. This will certainly result in a sharp increase in the use of plastics and intensify the release of microplastics to the surrounding ecosystems. Plastic consumption has increased dramatically (40%) and other applications (17%), including medical applications (Boroujeni et al. 2021).

Hospitals generate many infectious and biological wastes for sample collection of suspicious COVID-19 patients, testing, treating a significant number of people, and disinfection purposes. COVID-19 patients can produce around 3.4 kilograms of medical waste per day. Thus, during the epidemic, the amount of health waste has grown progressively (Das et al. 2021). For example, during the outbreak in Wuhan, China, over 245 metric tons of biological waste were created every day, over 190 metric tons more than usual. The number of healthcare waste generated in the Indian city of Ahmedabad grew from 500-600 kg day^{-1} to roughly 1000 kg day^{-1} during the first phase of the shutdown. COVID-19 generates approximately 206 million tons of biological waste a day in Dhaka, Bangladesh's metropolis (Celis et al. 2021). Other cities, including Kuala Lumpur, Manila, Hanoi, and Bangkok, had similar increases, creating between 154 and 280 million tons of medical waste each day compared to before the pandemic (Chakraborty and Maity 2020). Healthcare waste grew by 600% in Hubei, from 40 to 240 metric tons, overwhelming the infrastructure of transit and disposal. Similar difficulties face other countries as far as treating the enormous volume of garbage is concerned (Das et al. 2021).

Based on the review of the different papers, it can be assumed that perhaps the COVID-19 pandemic can have short-term favorable environmental benefits. However, the negative effects are much more severe. Many countries, particularly Australia, are grappling with the disposal of used personal protective equipment (PPE) composed of non-biodegradable plastics that really can take hundreds of years to degrade in the environment. According to the current study's estimates, in the first and second waves of the pandemic in Victoria, approximately 104-160 tons of the users' face masks were manufactured daily (Neumeyer et al. 2020). During the 2nd wave of the epidemic in Victoria, the respective mobility patterns of public transportation hubs, retail and entertainment venues, and workplaces decreased by 85, 83, and 76%, respectively, when contrasted to the period of 5 weeks between 3 January and 6 February 2020. $PM_{2.5}$ levels were also reduced by 23% at Alphington and 24% at Footscray (Aragaw 2020).

Personal protective equipment is a significant source of microplastics

Proper plastic disposal after they have been used has become a major concern. It is a setback in our campaign against plastic pollution as a whole. The products end up in locations where they are not supposed to be. They are common on the streets, in natural habitats, and in the oceans. People are desperately defending themselves from the illness; thus, masks are strewn across highways, sidewalks, and parks. If the masks make it to the oceans, they could endanger marine life. The proper disposal of PPE is also a concern (Oyedotun et al. 2020; Vanapalli et al. 2021). SARS-CoV-2 is more persistent on stainless steel and plastic than on cardboard and copper, and live virus particles can indeed be found up to 72 hours after being sprayed to these surfaces (Knowlton 2019). Although latex rubber gloves are natural items, there are concerns that they are not necessarily environmentally friendly. Chemicals employed in their production are hazardous to the environment and disposing of all such wastewater is another issue (Selvaranjan et al. 2021; Sridharan et al. 2021).

Face masks and other plastic-based protection equipment have been proposed as a possible source of microplastic fibers within the environment. N-95 masks are usually made up of polypropylene while Tyvek is used in protective gloves, suits, and medical face shields. Both the microplastics can last a long time and leak dioxin and harmful substances into the environment

(Selvaranjan et al. 2021; Sridharan et al. 2021; Wang et al. 2021b). Though specialists and responsible authorities recommend that domestic organic waste and plastic-based protective equipment be properly disposed of and segregated, mixing these wastes increases the danger of disease transmission and waste workers' exposure to the virus (Selvaranjan et al. 2021; Sridharan et al. 2021).

The usage of face masks triggered the microplastic release from 183 to 1247 particles/piece (Figure 4). The majority of microplastics liberated from face masks were clear medium-sized polypropylene fibers from nonwoven materials (Chen et al. 2021). Due to the wide distribution of microplastics likely to be exposed to heavy metals and organic pollutants in the natural environment, microplastics exhibit substantial potential for adsorption of harmful substances. Hydrophobic chemicals are adsorbed from environmental pollution onto the surface of the plastics (Ye et al. 2020). Some of those intentional chemical additives in plastics with toxic and endocrine-disrupting properties might be present at levels of 1-500 g kg^{-1} (Gallo et al. 2018). The estimated cumulative plastics marine debris can reach 250 million metric tons by 2025 (Jambeck et al. 2015).

Impacts of COVID-19 on water and soil ecosystems

Since the outbreak of the pandemic, non-steroidal anti-inflammatory prescription drugs (NSAIDs) are the most widely used pharmaceuticals in the globe, including nonselective cyclooxygenase (COX) inhibitors such as ibuprofen, naproxen, aspirin (acetylsalicylate), and diclofenac (WHO, 2020). Furosemide, a medication used for treating fluid retention, has been suggested for COVID-19 patients as a possible therapeutic disease through a primarily anti-inflammatory action mechanism (Brennecke et al. 2020). The ecosystem's components are intertwined with one another. People washing their hands with soap more frequently, government and local government mass disinfection, and the creation of single-use polymers with bisphenol A (BPA) all are destined to have severe effects on water and soil quality (Kim et al. 2021; Sridharan et al. 2021). Several laboratory experiments showed that human exposure to BPA would induce an endocrine disruption in many organ systems (Dodson et al. 2012). Alcohol-containing products spilled in water are dangerous to aquatic life, while spilled alcohol-containing products in the soil can pollute groundwater (Selvaranjan et al. 2021). Figure 5 shows the possible effects of emerging contaminants (e.g., anti-inflammatory chemicals, hydroxychloroquine/chloroquine, BPA, triclocarban, triclosan, etc.) on our soil and water environments, which are further triggered by the negative effects of COVID-19.

Triclocarban and triclosan are chemical compounds present in cleaning and washing products where they are used as antimicrobial and fungicides due to their high microbicide spectrum (Ley et al. 2018; Ion et al. 2019). These chemicals produce a barrier at the air-water contact by forming a protective surface coating. Both compounds are considered dangerous substances due to their potentially harmful effects on humans and marine ecosystems, as well as the possibility of creating antibiotic-resistant strains and have been banned in the USA by the Food and Drug Administration (FDA), but still appear on WWTP (Pycke et al. 2014; Sun et al. 2014).

Large quantities of effluent wastewater intoxicated with chloroquine and hydroxychloroquine were being discharged into the environmental waters, with potential ecotoxicological impacts on living organisms. According to Kuroda et al. 2021, the predicted environmental concentration (PEC) in raw wastewater for chloroquine, chloroquine metabolite (N-desethylchloroquine), and HCLQ were 857, 171, and 833 ng L^{-1}, respectively. PEC in secondary effluents for chloroquine, chloroquine metabolite (N-desethylchloroquine), and hydroxychloroquine were 320, 135, and 783 ng L^{-1}, respectively. Due to the assumed dilution, concentrations in the river waters were lowered by a factor of 10. Subsequently, the PEC for chloroquine, chloroquine metabolite (N-desethylchloroquine), and hydroxychloroquine in river water reduced to 32, 13, and 78.3 ng L^{-1}.

Moreover, eco-toxicological assessment for metabolites of both chloroquine and hydroxychloroquine found them to be highly persistent in the aquatic environment. Owing to their strong anti-viral and anti-bacterial properties, chloroquine, and its derivatives bioaccumulate their toxic forms in aquatic organisms. In terms of toxicological impact on the environment, the medium risk was predicted for hydroxychloroquine and N-desethylchloroquine (Kuroda et al. 2021).

Impacts of COVID-19 on aquatic life

Soaps are the earliest detergents known to man. Discharged detergents produce foam in bodies of water. Detergents and other soaps lower the surface tension of water, resulting in foam. Soaps can cut re-aeration by up to 40% (Capoor and Parida 2021). A study found that 120 mg L^{-1} of soap could reduce algal growth and development. Soaps can harm aquatic vegetation. Plants such as *Ranunculus aquatilis* and *Potamogeton* cannot thrive in detergent concentrations of 2.5 ppm (Ankit et al. 2021). The accumulation of toxic chemicals in the soil resulting from widespread soap use may degrade soil quality. The sudden rise in soapy discharge from every household over a short amount of time could increase the number of contaminants and change the composition of greywater. Domestic waste will damage river water, which will eventually damage lakes and seas. This unwelcoming series of events will become a severe problem (Leal Filho et al. 2021). Studies indicated that pharmaceuticals including naproxen, ibuprofen, diclofenac, and ketoprofen have been detected in the plasma of fish and marine organisms after they are exposed to treated wastewater (Vasquez et al. 2014). In the majority of traditional WWTPs, most of these emerging contaminants are not efficiently removed from wastewater. Effluent discharge and waste disposal on land might have long-term repercussions on our water systems and biota. Water and wastewater treatment systems for the removal of organic pollutants and emerging contaminants are thus necessary to be more effective and easily implemented. During the first stage of the COVID-19 pandemic, ibuprofen has been prescribed as an anti-inflammatory medicine to treat the symptoms of COVID-19 disease (De Girolamo et al. 2020; Yousefifard et al. 2020). Low levels of ibuprofen (~0.01 μg L^{-1}) have been observed to raise the danger to aquatic living things in the environment and can produce a serious persistent toxic impact on the reproduction of aquatics (Carlsson et al. 2006).

Impacts on the energy sources

The virus outbreak created several significant issues in the green energy industry, such as supply chain disruptions and tax stock market challenges (Jefferson 2020). Coal is one of the most significant fuels in the global energy market, occurring in up to 40% of electricity generation. Global coal output rises by 2.7% in 2018, with a projected annual production of 8.1 billion tons by 2019 (Rizou et al. 2020). Figure 6 (Ghosh 2020) shows that in 2020 the use of coal has decreased dramatically to 40 K metric tons, from 10–30 days following the new year, compared with 80 K metric tons before the COVID occurrence (Mousazadeh et al. 2021). Three major coal-producing countries, India, China, and Australia were primarily responsible for the growth, accounting for 70% of global production. The coronavirus lockdown is anticipated to increase world output by 0.5% in 2020 (Eroğlu 2020). However, the worldwide coal market is expected to shrink from $816.5 billion in 2019 to $722.8 billion in 2020 due to further lockdown and other government restrictions amid the ongoing COVID-19 outbreak (Chakraborty and Maity 2020). Several factors from the COVID-19 pandemic that have seriously disrupted oil demand would only trigger gradual recovery, thus curbing significant oil price increases due to market vulnerabilities for at least three years (Jefferson 2020).

The global economic slowdown impact of global lockdown to stop the spread of the Covid-19 epidemic is largely to blame for this huge drop in global output. Similarly, global oil consumption was severely impacted, with a 5% drop in the first quarter of 2020 (Atolani et al. 2020). The drop was primarily due to restrictions on transportation and aircraft, which together account for more than 60% of world oil demand. Similarly, lockdown measures have resulted in a large reduction in electricity usage (>20%), with knock-on implications on the energy mix (Boroujeni et al. 2021). After 40 days of lockdown, Italy showed up to a 30% reduction in energy usage. In France, Germany, Spain, India, and the United Kingdom, there are 15, 12, 15, 20, and 16% reductions in power usage, as shown in Figure 7 (IEA 2021; Mousazadeh et al. 2021). Less energy usage resulted in some positive impacts on the environment regarding various air pollutants (Figure 1). Due to less energy usage, reduced emissions of air pollutants such as greenhouse gases as discussed previously (Adams 2020; Chen et al. 2020; Li et al. 2020; Liu et al. 2021) and particulate matter were noted during COVID-19 (Shen et al. 2021a). Reduced emissions of NO_2 in the atmosphere resulted in an improved air quality index around the world (Lian et al. 2020).

Mitigating the negative impacts of the pandemic

Hazardous wastes guidelines and policies during the pandemic

Various national and international agencies have given the guidelines to mitigate the negative impacts of pandemic waste. For example, WHO (2020) has advised the workers to wear proper personal protective equipment (PPE) for the safe collection and disposal of pandemic wastes. US-EPA (2020) has focused on recycling and sustainable management of food wastes at public and private institutions during the pandemic. The U.S Occupational Safety and Health Administration (OSHA), 2020 has advised to have strict engineering and administrative controls, safe work practices, and proper PPE during pandemic waste handling. European Commission, 2020 has also stressed on safe handling of pandemic waste generated from households with confirmed cases and the safety of workers involved in pandemic waste collection. In the United Kingdom, waste stream prioritization, expansion in the temporal waste capacity, waste segregation, an adaptation of MSW incinerators to dispose of COVID-19 infectious waste, and communication with residents were recommended (DEFRA, 2020).

In India, the safety of workers with proper PPE, the dedicated vehicle involved in pandemic waste collection, quarantine facilities at Common Bio-medical Waste Treatment Facilities, and proper labeling was recommended by CPCB (2020). The Ministry of Ecology and Environment of the People's Republic of China recommended proper packing of pandemic wastes, the establishment of medical waste disposal units, incinerators, furnaces, emergency disposal methods, and standards for pollution control on medical waste treatment and disposal (GB39707-2020). According to Nigeria's Center for Disease Control (NCDC) guidelines, special waste collection bins, daily disposal, and decontamination as per standard protocols were recommended. Despite these recommendations by different agencies, various strategies have been employed to properly the pandemic waste. The details about these strategies are given in the following sections.

Strategies for the management of solid wastes

Hospitals and health care centers have generated a tremendous amount of infectious and biological waste for sample collection of suspicious COVID-19 patients, testing, treating a significant number of people, and disinfection purposes. Thus, more efficient and cost-effective disposal methods for the disposal of medical wastes are urgently needed during the pandemic and post-pandemic periods. Effective healthcare waste management is entirely based on a well-organized and well-executed management strategy. To create and maintain an effective waste management strategy, a waste management team or panel should be created. An infection control committee, with one individual involved in healthcare waste management in healthcare institutions, should be established in low-income regions (Das et al. 2021; Hantoko et al. 2021). After the safe disposal of waste, the PPE must be removed safely, and the sanitizer used for disinfecting hands after the waste has been disposed of. For safe cleaning off-site or on-site, the soiled PPE must be placed in a sealed bag and should be cleaned with an agent containing 10% lime slurry (WHO, 2020). Several countries have current regulations and protocols for the disposal of the hospital or domestic medical waste. During the COVID-19 epidemic, certain modifications were made to the waste management method (Hantoko et al. 2021). The trends and practices for solid waste management during the COVID-19 pandemic are presented in Figure 8 (ACRPlus 2020).

Thermochemical conversion processes for treating medical wastes

COVID-19 contributed to the worldwide massive increase of medical waste, generated largely by clinics, hospitals, and other healthcare facilities. This poses another hurdle in the management of medical waste, especially in poor nations. Inappropriate medical wastes management might have severe public health problems and major environmental consequences (Das et al. 2021; Dharmaraj et al. 2021). Thermochemical conversions (i.e., pyrolysis, gasification, hydrothermal liquefication) of solid wastes including medical wastes, offer several advantages through recovering the recourses and energy and stabilizing/destructing the toxins/contaminants and microplastics in the precursors (Mohamed et al. 2017, 2022a). Pyrolysis is generally non-selective, and many products, including biochar, bio-oil, and gases, can be created in a very short time among all other thermochemical conversion processes (Mohamed et al. 2021; Huang et al. 2022; Periyasamy et al. 2022). Fast pyrolysis has been explored mainly to produce bio-oil, with a maximum yield of > 70%. Furthermore, the method is more environmentally friendly, reliable, and cost-effective, needs almost no landfill capacity, and produces fewer pollutants (Leng et al. 2022; Mohamed et al. 2022a, b). The use of catalytic pyrolysis to improve the quality of pyrolysis vapors, especially bio-oil and noncondensable gases, has been widely researched. Natural and synthetic zeolites are among the numerous catalysts available that have been investigated for improving bio-oil quality (Pütün et al. 2006; Sulman et al. 2009; Veses et al. 2015).

During the pyrolysis process, the plastic waste itself has an impact on the product composition. The primary components found in the waste of COVID-19 plastics included polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). These cross-linked polymers in the plastic wastes do not melt during high-temperature pyrolysis; instead of melting, they produce valuable energy-bearing products including bio-oil-rich hydrocarbons, gases rich in hydrogen gas content, and charcoal (Dharmaraj et al. 2021; Zhou et al. 2021). The generation of lighter and thermodynamically stable hydrocarbons including aromatic hydrocarbons and C_1-C_4 gases was triggered by higher pyrolysis temperatures (Figure 9). The resistance to thermal decomposition of three distinct plastic feedstocks was ranked as follows based on product yields and chemical composition: HDPE, PP, and PP with fillers, with the mineral filler, talc, acting as a catalyst and showing considerable cracking activity (Zhou et al. 2021).

The pyrolysis treatment utilizing the face masks was presented by the authors as a safe and cost-effective way to dispose of face masks that protect against Covid-19 (Yousef et al. 2021). Pyrolysis of face masks was conducted using TG-FTIR-GC–MS method, and the results revealed that the face mask has high volatiles with high mass loss of 67–96%, which decomposed in three stages between 360 and 500 ºC with activation energy ranging from 231 to 281 kJ mole^{-1}. Based on the GC/MS results, the bio-oil produced from the face mask is composed mainly of furan, propene, isopropylcyclobutane, and 2,4-dimethyl- 1-heptene (Yousef et al. 2021).

Thermochemical conversion processes for treating sewage sludge

The majority of the traditional WWTPs are not much efficient in removing most of the emerging contaminants and microplastics from wastewater effluent and sludge/biosolids (Mohamed et al. 2022a). Therefore, traditional WWTPs increase the possibility of spreading hundreds of contaminants and microplastics/nanoplastics in the aquatic ecosystems and agricultural lands in case of using biosolids as fertilizer (Kimbell et al. 2018; Patel et al. 2019; Rodríguez-Narvaez et al. 2021). Thus, advanced treatment methods for removing organic pollutants and emerging contaminants are needed, which should be more effective and can be easily implemented without creating secondary wastes and/or toxic pollutants. However, some advanced treatment methods could further generate more byproducts with high acute toxicity for marine creatures and humans such as benzoquinone (Reddy et al. 2018).

Among several treatment methods, thermochemical conversion processes i.e., pyrolysis, gasification, hydrothermal liquefaction have proved more effective for the destruction and/or stabilization of toxins (Kimbell et al. 2018), viruses, emerging contaminants (Xu et al. 2015; Murtaza et al. 2021; Mehmood et al. 2022), and microplastics (Rodríguez-Narvaez et al. 2021) as shown in Figure 10. Microplastics in the sludge are considered a good source for carbon-based materials that can be utilized as a precursor for the manufacturing of sludge-based adsorbents (e.g., hydrochar, biochar, activated carbon) with possibilities for environmental usages for treating contaminated sites or wastewater effluents (Xu et al. 2015; Rodríguez-Narvaez et al. 2021). Several studies successfully produced sludge-based adsorbents with very high BET surface area >1800 m^2 g^{-1} (Xu et al. 2015). Furthermore, during pyrolysis operations, the generated volatiles and gases could be collected, condensed into biofuels, and used as a source of sustainable energy to maximize profits (Figure 10) (Mohamed et al. 2019). Li and coworkers developed a method combining hydrothermal pretreatment, anaerobic digestion, and pyrolysis to fully utilize sewage sludge from WWTPs, and the process was evaluated at the pilot scale. It was found that the heavy metals were stabilized and the process is effective for resources and energy recovery from sewage sludge (Li et al. 2018). However, it is necessary to analyze the potential of releasing original contaminations in the sludge, which could transform, volatilize or decompose to new forms of hazardous substances during the sludge-based adsorbents production process (Xu et al. 2015).

Strategies for the management of pharmaceutical and personal care products

Various strategies such as photocatalytic degradation (Kargar et al. 2021), electrochemical advanced oxidation (Tella et al. 2018; Rizvi and Ahammad, 2022), metal-organic framework, and carbon biomasses adsorbents (Rasheed et al. 2020; Gümüş and Gümüş, 2021; Januário et al. 2022) and microbial degradation (Lindroos et al. 2019) have been employed for the removal of various pharmaceutical and personal care products in water and soil ecosystem. Previous studies have utilized different sorbent materials (biochar, activated carbon) to remove ibuprofen and naproxen. The corresponding removal efficiencies range from 83 to 99% (Chakraborty et al. 2018; Tomul et al. 2020; Kim et al. 2021), with the highest removal observed for biochar, produced from peanut shell (Tomul et al. 2020). A sludge-based biochar was produced from the co-pyrolysis of sewage sludge and bamboo waste and was successfully used to remove 95% of antibiotic residues (e.g., ciprofloxacin) (Li et al. 2020). Sludge-based biochar was also successfully used as a heterogeneous Fenton-like catalyst for the degradation of organic contaminants (Li et al. 2019).

Despite there are several studies that report the presence of pharmaceutical and personal care products in effluents, an international framework regarding WWTP effluents guidelines is needed. In fact, just a few countries regulate wastewater discharges. For example, Canada inspects BPA (3.5 µg/L) and triclosan (0.47 µg/L), in Federal Environmental Quality Guidelines, which are recommendations in quantitative or qualitative terms to support federal environmental quality monitoring (FEQGs, 2020); China regulates only BPA (0.01 mg/L) (EPPRC, 2002) as an ecological hazard value. Thus, it is essential to regulate the concentrations of the harmful pharmaceutical and personal care products in the final discharged wastewater effluent before being discharged into receiving the receiving waters.

Outlook and future directions

A cross-disciplinary collaborative strategy is urgently required to address the existing environmental concerns created by the indirect detrimental effects of the COVID-19 pandemic. There is a need to lessen reliance on single-use PPE or trash caused by pandemics. Repurposing worn PPE is an excellent strategy to avoid dumping a large volume of pandemic-related garbage in landfills (Dharmaraj et al. 2021). The researchers have already conducted a feasibility study on using shredded face masks combined with recycled concrete as a road surface material. According to the findings, constructing a two-lane 1-kilometer road would necessitate the usage of nearly 3 million old face masks, which would otherwise end up in landfills. It was also discovered that reusing the used masks improved the quality of the recycled masks (Somani et al. 2020).

To accommodate surplus healthcare waste, mobile treatment and temporary storage strategies may aid sustainable management of healthcare waste without further spreading the virus. Proper healthcare waste management can also help to recycle waste or convert it into valuable products, e.g., energy. Hazardous medical wastes should be treated through thermal treatment such as pyrolysis or gasification to recover more energy with less carbon footprint, and care should be taken because of the possible release of toxic chlorinated gases and other toxic gases.

Pollution from the environment is a significant risk factor and helps to increase the prevalence of major chronic diseases. The COVID-19 pandemic determines the need for a constructive approach, in particular the implementation of environment-friendly policies focused on air pollution reduction and the safe disposal of medical hazardous wastes. Further investigation is necessary for the study of the probable presence of coronavirus and other viruses in municipal and drinking water and the development of effective water analytical technologies (La Rosa et al. 2020). In addition to health education regarding disinfections and managing municipal solid waste with a scientific basis, clear instructions on the treatment of domestic medical waste are required (Das et al. 2021).

Conclusions

Perhaps the COVID-19 pandemic has short-term favorable environmental benefits. However, the environmental issues resulting from this virus outbreak could have long-lasting effects and post challenges for all countries around the world. COVID-19 has also posed negative consequences on the water and soil ecosystem due to the significant usage of antibacterial hand sanitizers, disinfectants, and medications, increasing the accumulation of various toxic emerging contaminants including triclocarban, triclosan, and hydroxychloroquine. Face masks and other plastic-based protection equipment have been found as major sources for the release and accumulation of microplastics in the aquatic/terrestrial ecosystems, posing major threats for aquatics and humans. Proper handling of municipal solid waste, including medical wastes and treated sludge/biosolids, may lead to a viable energy source and thereby will achieve environmental sustainability. Thermochemical conversion processes including pyrolysis and gasification could be utilized effectively for the destruction and/or stabilization of toxins, viruses, emerging contaminants, and microplastics present in the sludge and solid waste, and energy and resources recovery from the precursors. The information presented in this review can be used to assess short and long-term options for mitigating future harmful effects.

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Author Contributions Statement

Badr Mohamed: Conceptualization; Methodology; Data curation; Formal analysis; Writing - original draft; **I M Rizwanul Fattah:** Methodology; Conceptualization, Writing - review & editing; **Balal Yousaf:** Conceptualization; Writing - review & editing; **Selvakumar Periyasamy:** Conceptualization; Writing - review & editing

Data availability

All data analyzed during this study were included in this article.

Compliance with Ethical Standards

Conflict of interest

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

Ethical approval

This article does not involve any Human Participants and/or Animals.

Informed consent

Not applicable.

Consent to participate and publish

All authors participated and approved the final manuscript to be published.

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Figures

Fig. 1: Box and Whisker plot showing the reduction of different air pollutants in different countries during lockdown

Fig. 2: Johns Hopkins University CSSE is tracking the spread of SARS-CoV-2 in near real time with a map-centric dashboard (using ArcGIS Online). Screenshot date: 26 October 2021.

Fig. 3: Time series suspended particulate matter (SPM) concentrations (2013–2020) estimated for the Vembanad lake, reproduced with permission from Elsevier (Yunus et al., 2020).

Fig. 4: Abundances and proportions of microplastics in different colors released from the new and used disposable face masks: a) and c) including transparent; b) and d) colored microplastics; types of polymer in different colors of microplastics identified by Raman spectrum (e), reproduced with permission from Elsevier (Chen et al., 2021)

Fig. 5: COVID-19 triggered the accumulation of the harmful emerging contaminants in our soil and water environments.

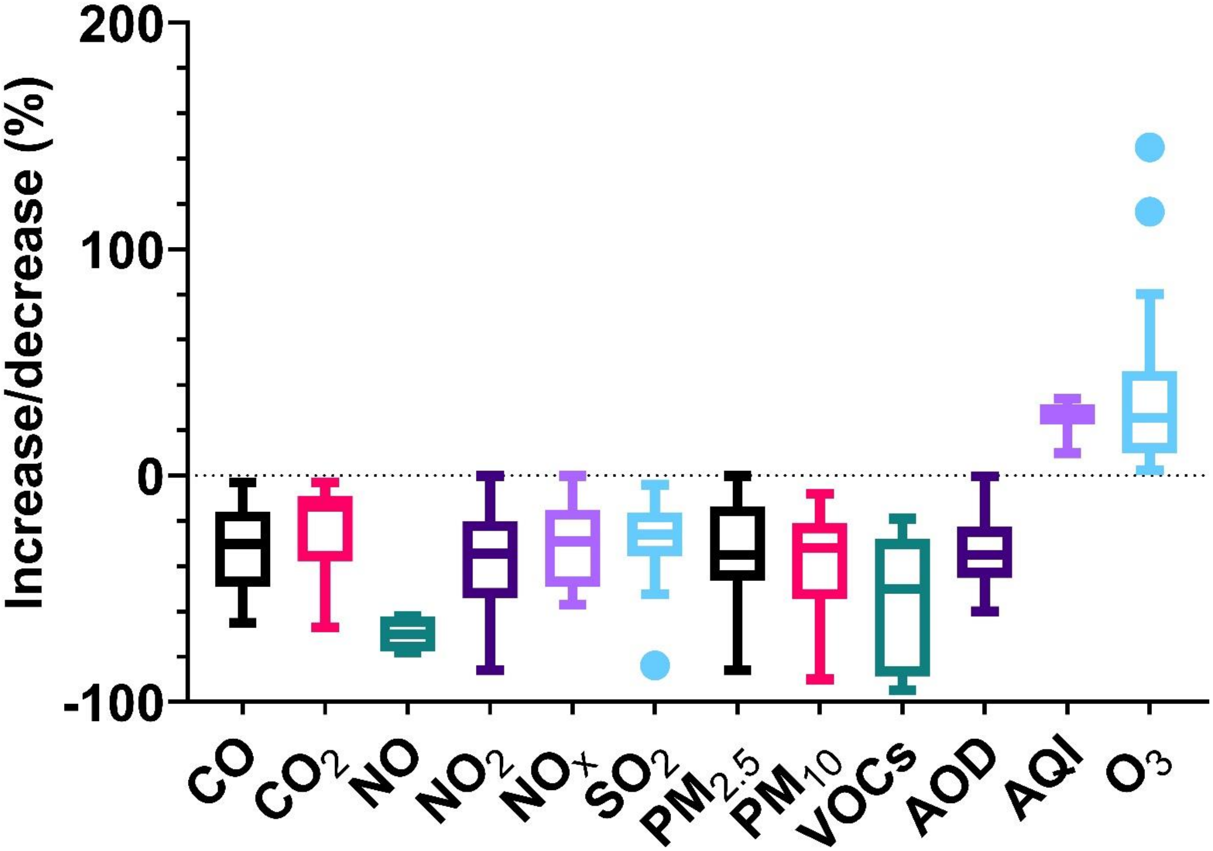
Fig. 6: Use of coal fuel in China in 2016–2020. The consumption drop for all years during the Chinese new year is explained by holidays with industrial shutdowns (Ghosh, 2020).

Fig. 7: The decline in electricity during COVID-19 lockdown: (a) Weather-corrected electricity demand compared in China, India and Europe (weighted average of France, Germany, Italy, Spain); (b) Commercial and industrial electricity demand; and (c) Historical and expected changes until 2022 (IEA, 2021).

Fig. 8: Management practices of solid waste during COVID-19 pandemic, adapted from (ACRPlus, 2020).

Fig. 9: Product yields (a), gas product compositions (b), liquid product compositions (c) and liquid product carbon number distributions (d) of thermal pyrolysis of three different types of plastic feedstock (i.e., HDPE, pure PP and PP with fillers) at 620 °C, reproduced with permission from Elsevier (Zhou et al., 2021)

Fig. 10: Thermochemical conversion processes as a promising route for treating sewage sludge and solid wastes to produce biofuel.



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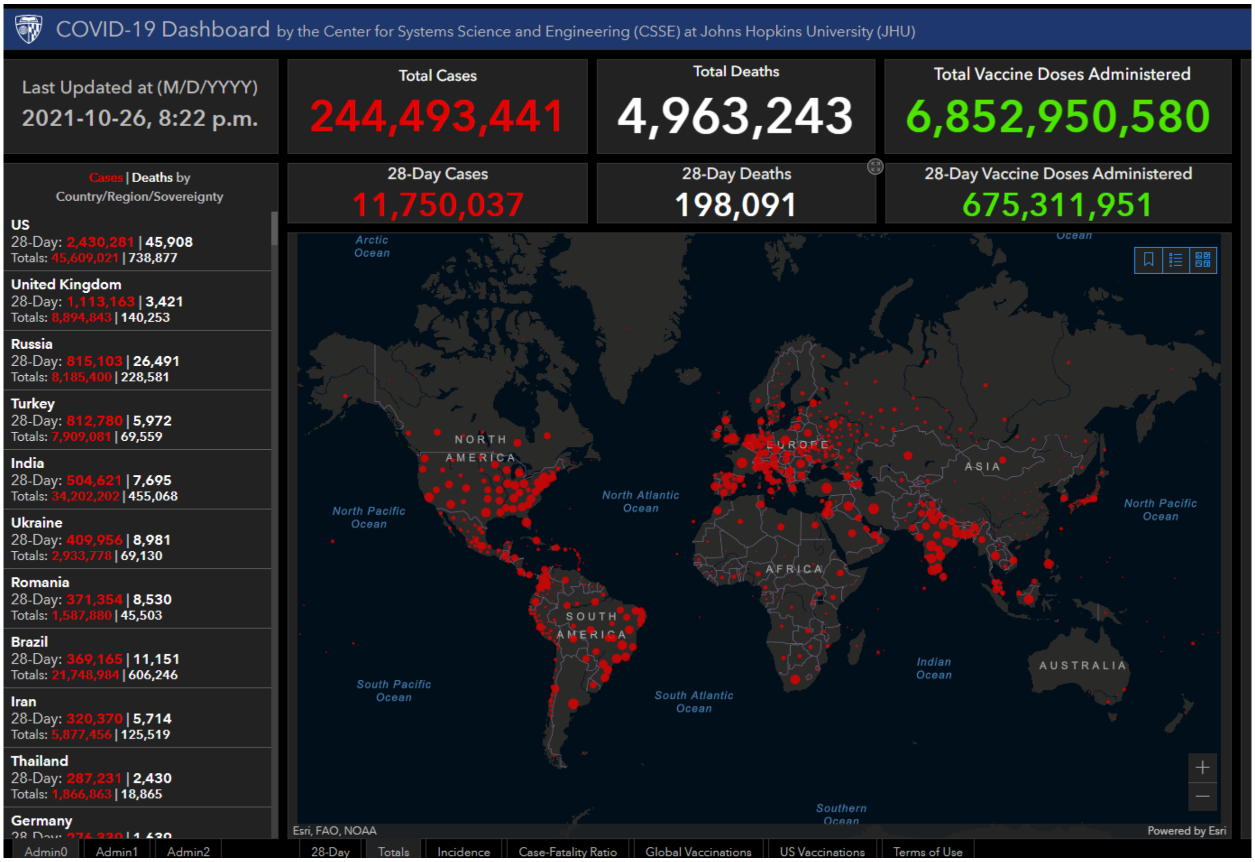


COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU)

Last Updated at (M/D/YYYY)
2021-10-26, 8:22 p.m.

Total Cases
244,493,441

Total Deaths
4,963,243

Total Vaccine Doses Administered
6,852,950,580

28-Day Cases
11,750,037

28-Day Deaths
198,091

28-Day Vaccine Doses Administered
675,311,951

Cases | Deaths by Country/Region/Sovereignty

US
28-Day: 2,430,281 | 45,908
Totals: 45,609,021 | 738,877

United Kingdom
28-Day: 1,113,163 | 3,421
Totals: 8,894,843 | 140,253

Russia
28-Day: 815,103 | 26,491
Totals: 8,185,400 | 228,581

Turkey
28-Day: 812,780 | 5,972
Totals: 7,909,081 | 69,559

India
28-Day: 504,621 | 7,695
Totals: 34,202,202 | 455,068

Ukraine
28-Day: 409,956 | 8,981
Totals: 2,933,778 | 69,130

Romania
28-Day: 371,354 | 8,530
Totals: 1,587,880 | 45,503

Brazil
28-Day: 369,165 | 11,151
Totals: 21,748,984 | 606,246

Iran
28-Day: 320,370 | 5,714
Totals: 5,877,456 | 125,519

Thailand
28-Day: 287,231 | 2,430
Totals: 1,866,863 | 18,865

Germany

Fig. 2: Johns Hopkins University CSSE is tracking the spread of SARS-CoV-2 in near real time with a map-centric dashboard (using ArcGIS Online). Screenshot date: 26 October 2021.

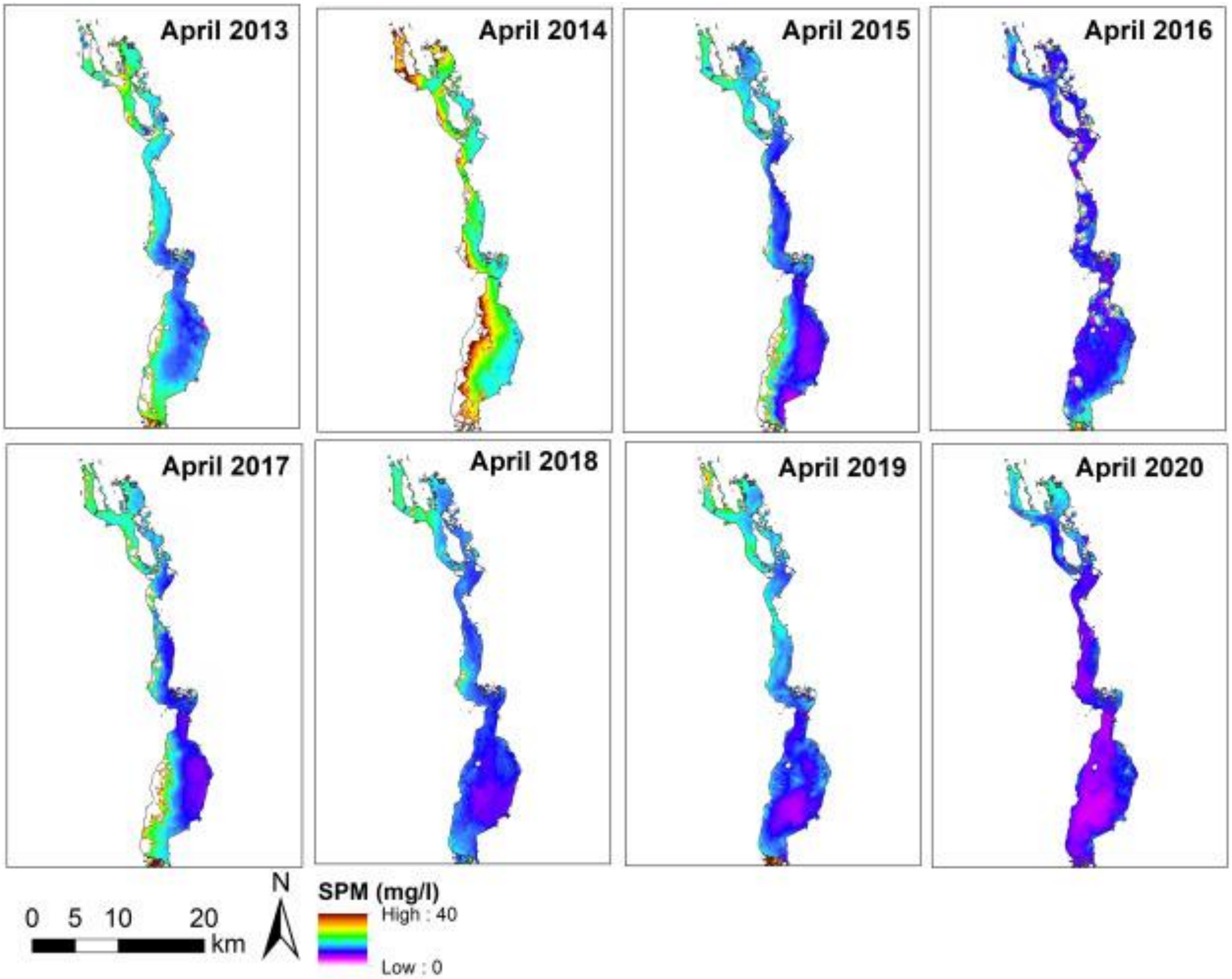


Fig. 3: Time series suspended particulate matter (SPM) concentrations (2013–2020) estimated for the Vembanad lake, reproduced with permission from Elsevier (Yunus et al., 2020).

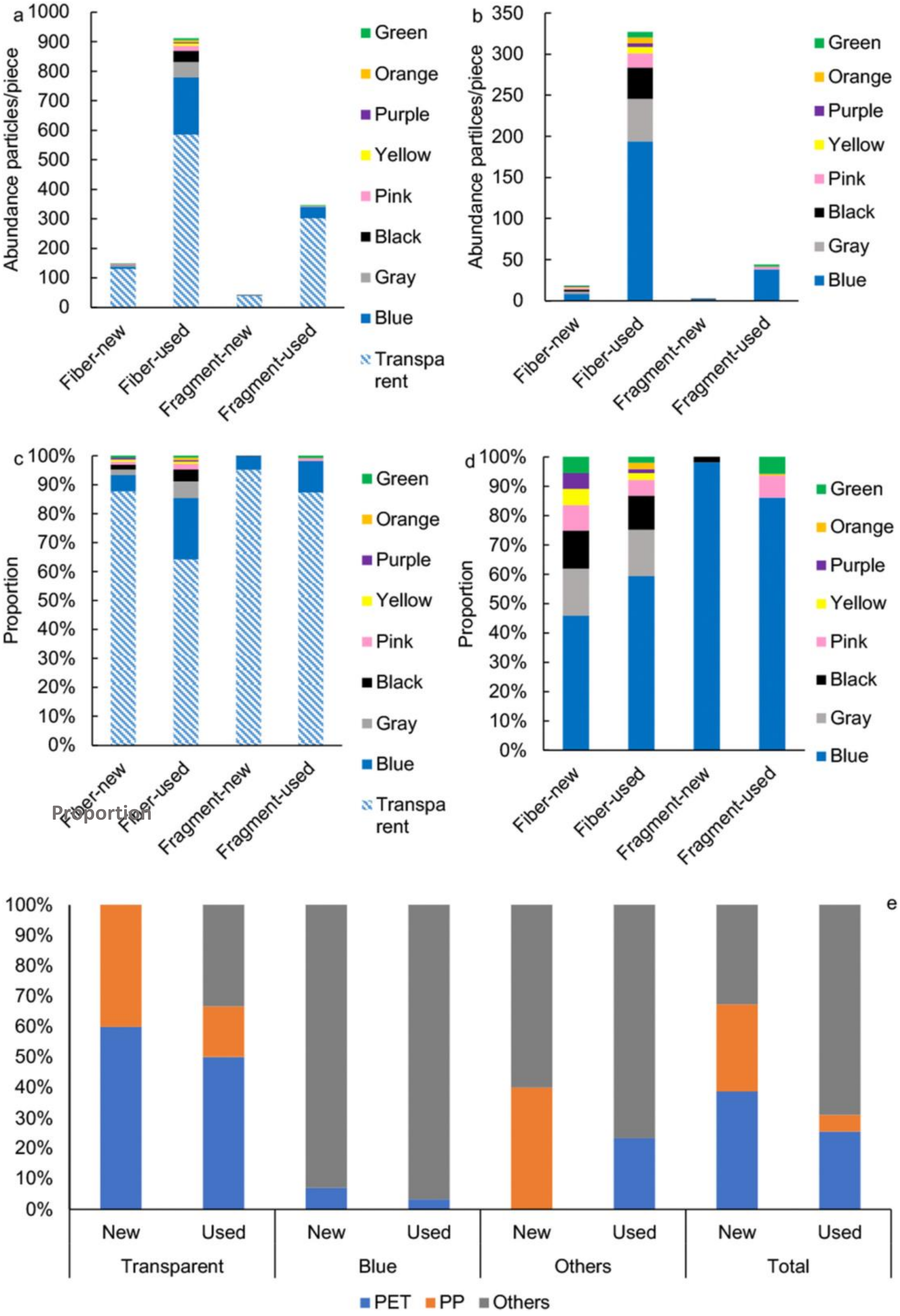


Fig. 4: Abundances and proportions of microplastics in different colors released from the new and used disposable face masks: a) and c) including transparent; b) and d) colored microplastics; types of polymer in different colors of microplastics identified by Raman spectrum (e), reproduced with permission from Elsevier (Chen et al., 2021)

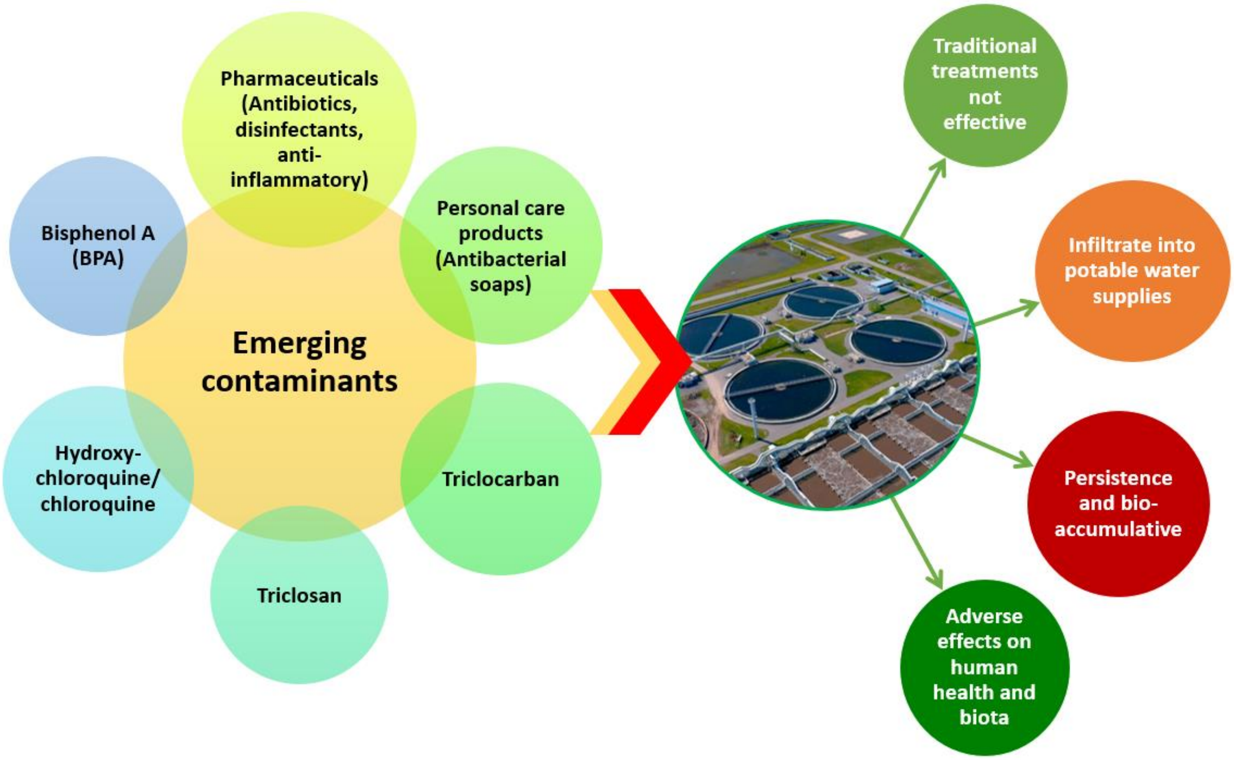


Fig. 5: COVID-19 triggered the accumulation of the harmful emerging contaminants in our soil and water environments.

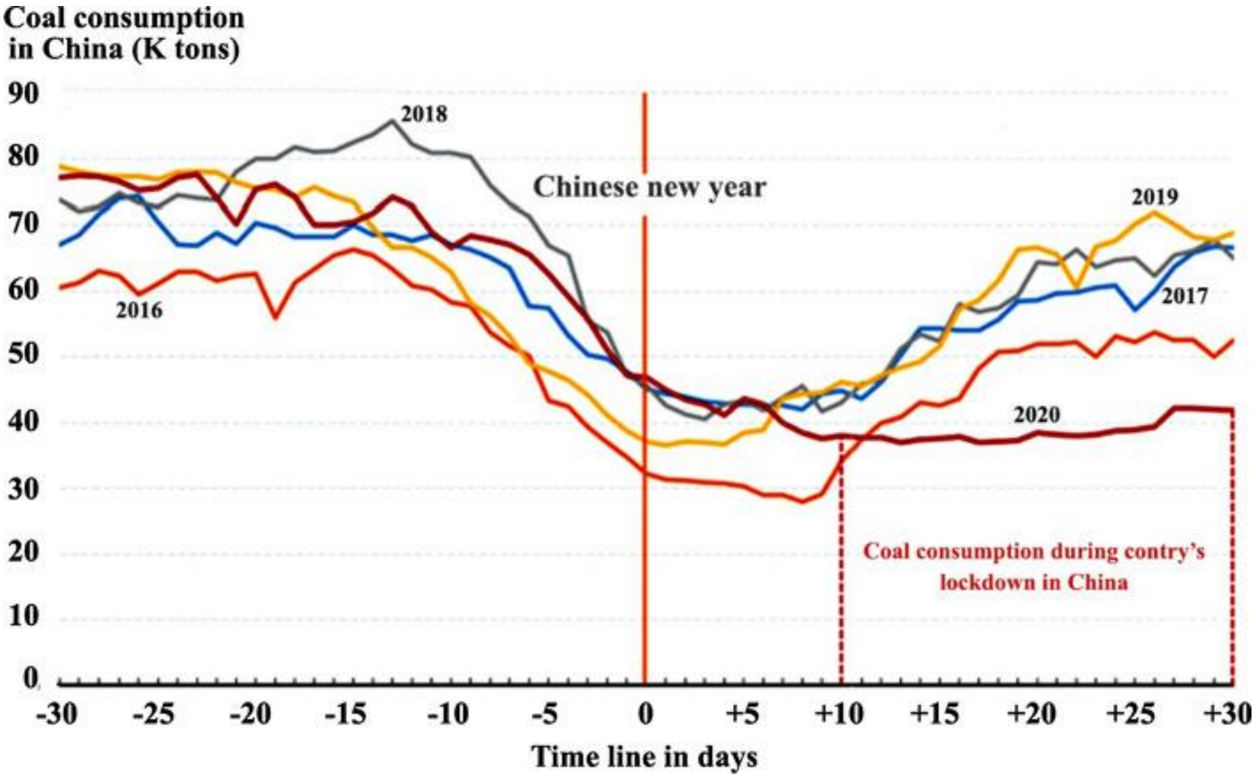


Fig. 6: Use of coal fuel in China in 2016–2020. The consumption drop for all years during the Chinese new year is explained by holidays with industrial shutdowns (Ghosh, 2020).

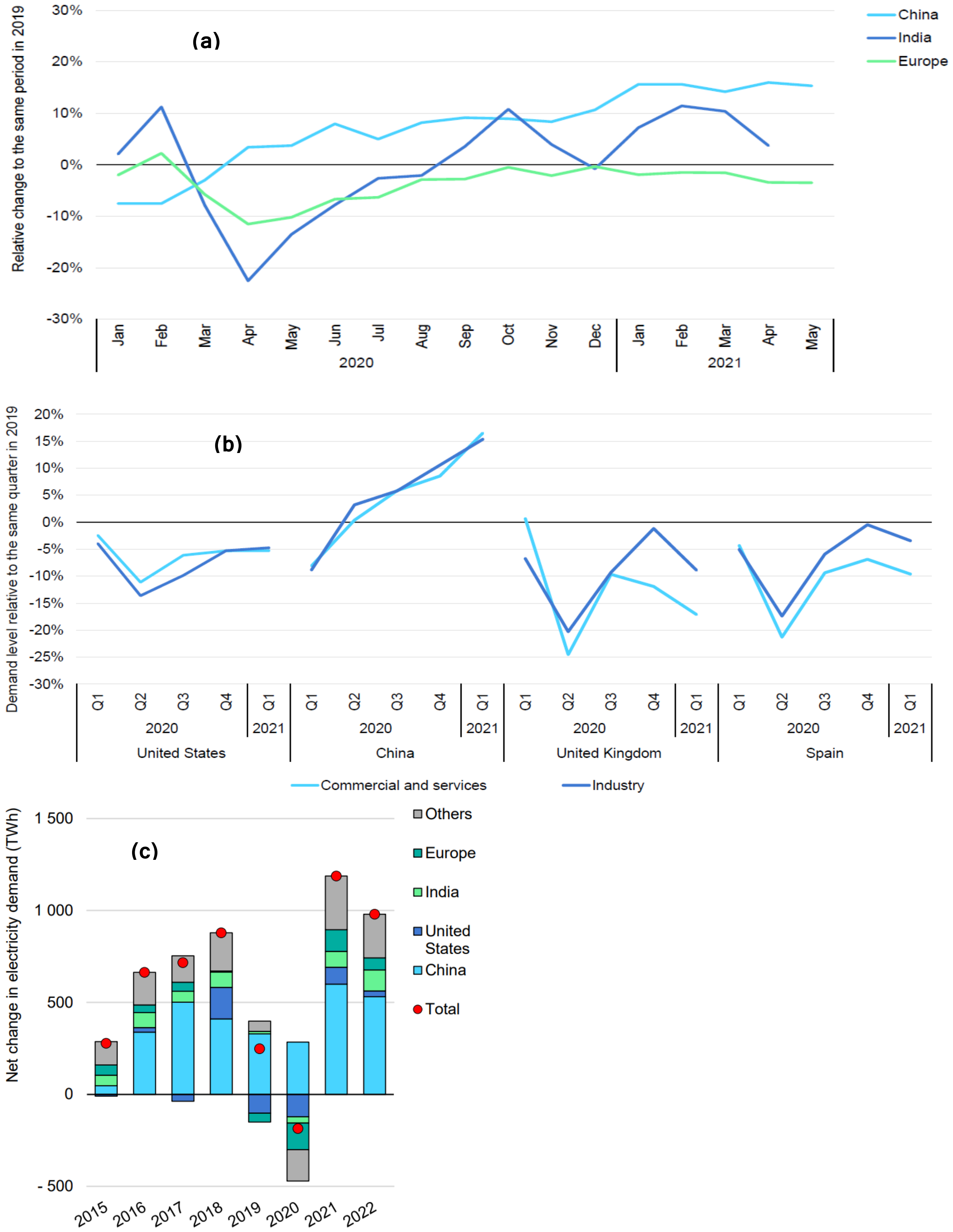


Fig. 7: The decline in electricity during COVID-19 lockdown: (a) Weather-corrected electricity demand compared in China, India and Europe (weighted average of France, Germany, Italy, Spain); (b) Commercial and industrial electricity demand; and (c) Historical and expected changes until 2022 (IEA, 2021).

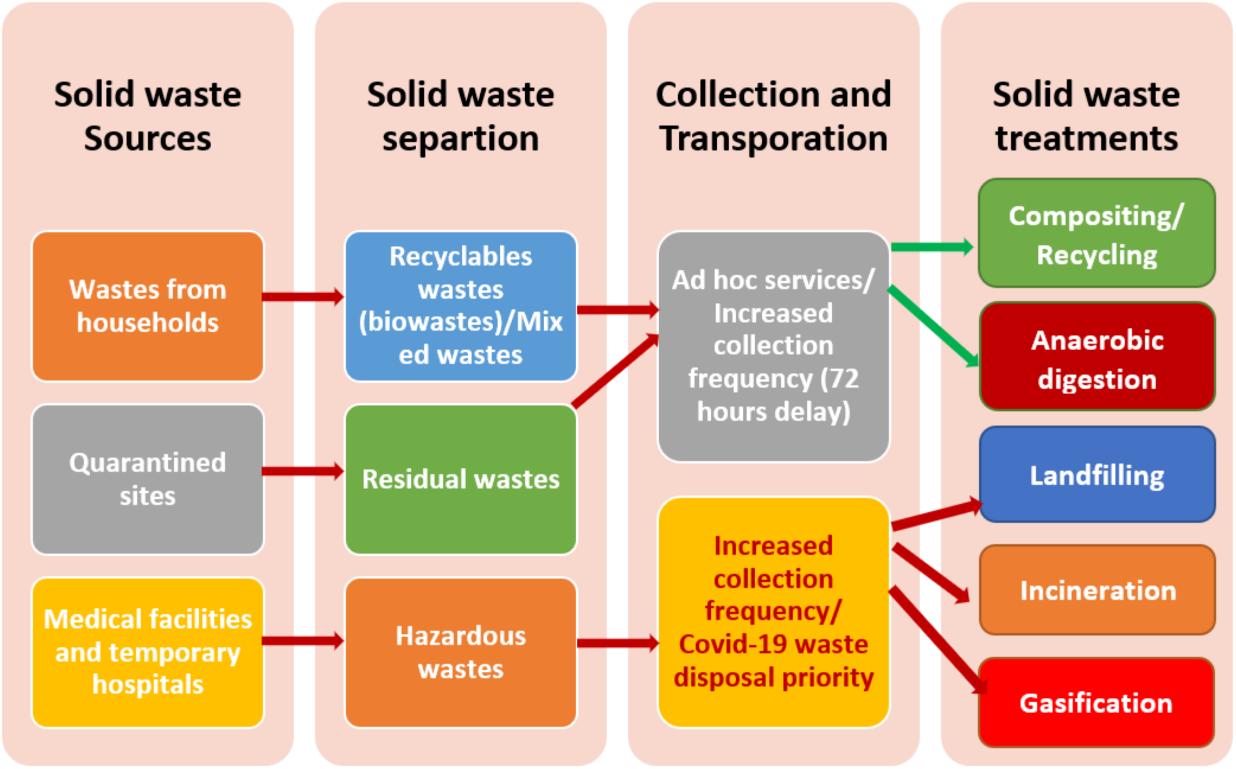
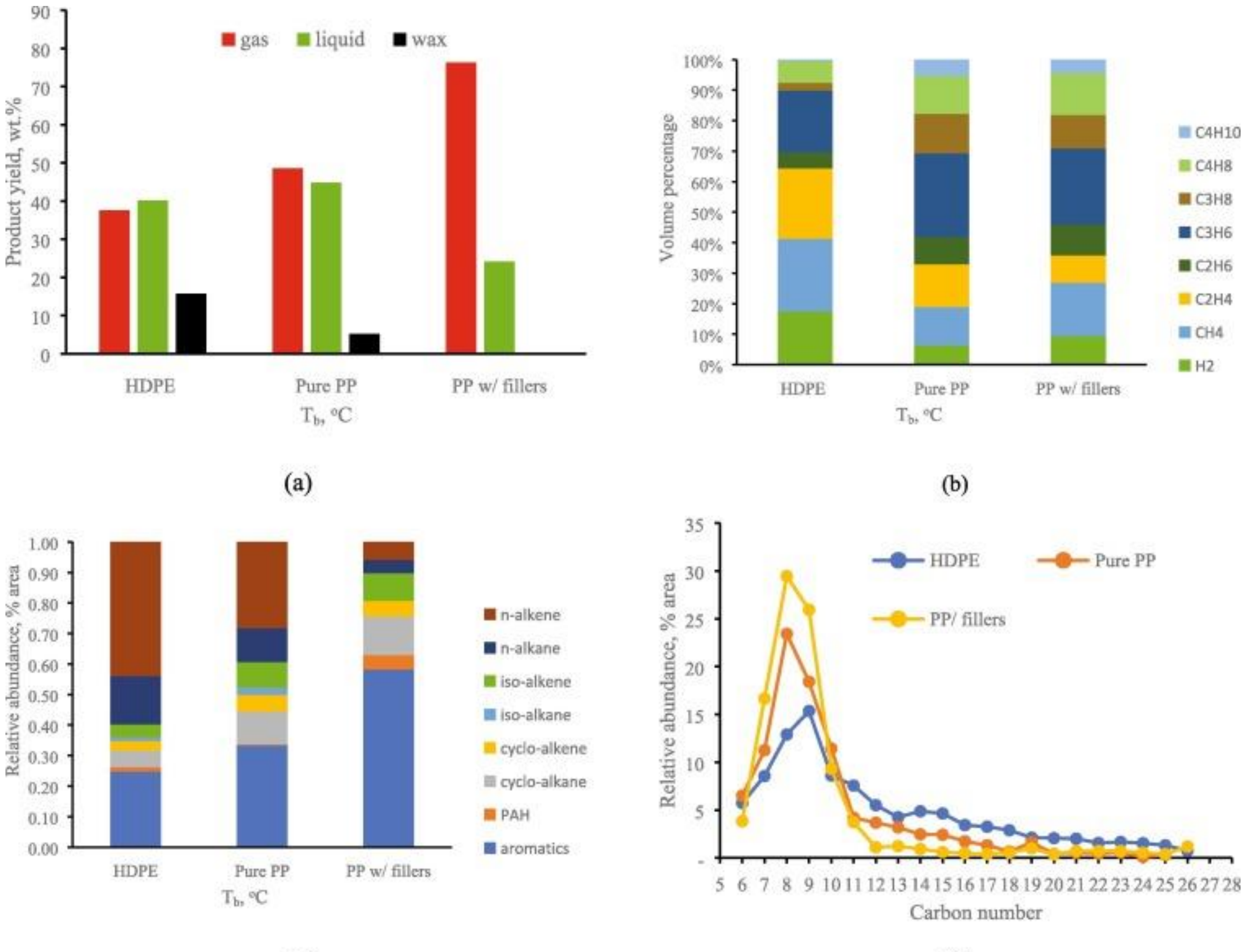


Fig. 8: Management practices of solid waste during COVID-19 pandemic, adapted from (ACRPlus, 2020).



(a) (b)

(c) (d)

Fig. 9: Product yields (a), gas product compositions (b), liquid product compositions (c) and liquid product carbon number distributions (d) of thermal pyrolysis of three different types of plastic feedstock (*i.e.*, HDPE, pure PP and PP with fillers) at 620 °C, reproduced with permission from Elsevier (Zhou et al., 2021)

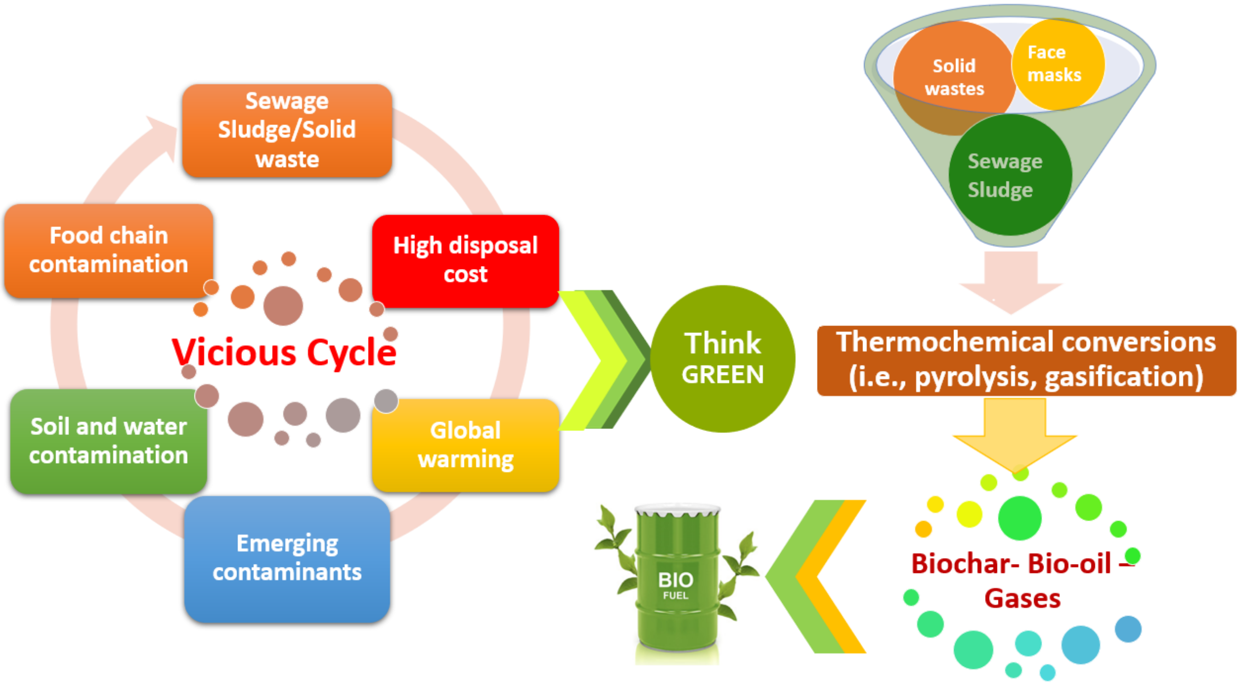


Fig. 10: Thermochemical conversion processes as a promising route for treating sewage sludge and solid wastes to produce biofuel.