Understanding temporary reduction in atmospheric pollution and its impacts on coastal aquatic system during COVID-19 lockdown: a case study of South Asia

Muhammad Shafeeqe, Arfan Arshad, Ahmed Elbeltagi, Abid Sarwar, Quoc Bao Pham, Shahbaz Nasir Khan, Adil Dilawar, and Nadhir Al-Ansari

Key Lab of Ecosystem Network Observation and Modelling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China; University of Chinese Academy of Sciences, Beijing, China; Department of Irrigation and Drainage, Faculty of Agricultural Engineering, University of Agriculture Faisalabad, Faisalabad, Pakistan; Key Laboratory of Digital Earth Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing, China; Agricultural Engineering Department, Faculty of Agriculture, Mansoura University, Mansoura, Egypt; College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, China; Institute of Research and Development, Duy Tan University, Danang, Vietnam; Faculty of Environmental and Chemical Engineering, Duy Tan University, Danang, Vietnam; Department of Structures and Environmental Engineering, Faculty of Agricultural Engineering, University of Agriculture Faisalabad, Faisalabad, Pakistan; LREIS, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China; Department of Civil, Environmental and Natural Resources Engineering, Lulea University of Technology, Lulea, Sweden

ABSTRACT

The strict lockdown measures not only contributed to curbing the spread of COVID-19 infection, but also improved the environmental conditions worldwide. The main goal of the current study was to investigate the co-benefits of COVID-19 lockdown on the atmosphere and aquatic ecological system under restricted anthropogenic activities in South Asia. The remote sensing data (a) NO2 emissions from the Ozone Monitoring Instrument (OMI), (b) Aerosol Optical Depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS), and (c) chlorophyll (Chl-a) and turbidity data from MODIS-Aqua Level-3 during Jan–Oct (2020) were analyzed to assess the changes in air and water pollution compared to the last five years (2015–2019). The interactions between the air and water pollution were also investigated using overland runoff and precipitation in 2019 and 2020 at a monthly scale to investigate the anomalous events, which could affect the N loading to coastal regions. The results revealed a considerable drop in the air and water pollution (30–40% reduction in NO2 emissions, 45% in AOD, 50% decline in coastal Chl-a concentration, and 29% decline in turbidity) over South Asia. The rate of reduction in NO2 emissions was found the highest for Lahore (32%), New Delhi (31%), Ahmadabad (29%), Karachi (26%), Hyderabad (24%), and Chennai (17%) during the strict lockdown period from Apr–Jun, 2020. A positive correlation between AOD and...
and NO₂ emissions (0.23–0.50) implies that a decrease in AOD is attributed to a reduction in NO₂. It was observed that during strict lockdown, the turbidity has decreased by 29%, 11%, 16%, and 17% along the coastal regions of Karachi, Mumbai, Calcutta, and Dhaka, respectively, while a 5–6% increase in turbidity was seen over the Madras during the same period. The findings stress the importance of reduced N emissions due to halted fossil fuel consumption and their relationships with the reduced air and water pollution. It is concluded that the atmospheric and hydro-spheric environment can be improved by implementing smart restrictions on fossil fuel consumption with a minimum effect on socioeconomics in the region. Smart constraints on fossil fuel usage are recommended to control air and water pollution even after the social and economic activities resume business-as-usual scenario.

Introduction

Environmental pollution is an alarming problem around the globe, and it is getting even more prominent in fast-growing developing countries due to the excessive use of fossil fuels in transportation and industries as a result of fast-growing human demands (Dhar and Shukla 2015; Fullerton et al. 2008; Gordon et al. 2014; Wang and Hao 2012). Around the globe, the most polluted cities with dense populations are located in Asia (Beig et al. 2020; Conticini et al. 2020; Gao et al. 2020; Maji 2020; Mathur et al. 2020; Yousefian and Nadafi 2019). Given the elevated air pollution in these cities, poor air quality may cause cellular inflammation, severe respiratory problems, bronchial hyper-responsiveness, and eventually death (Lippmann and Leikauf 2020; Shang et al. 2020; Yang et al. 2020). According to the World Health Organization (WHO), more than 4.6 million people die annually due to poor air quality standards worldwide. In intensively urbanized regions, atmospheric nitrogen dioxide (NO₂) and urban aerosols are among the most discussed and hazardous air pollutants (Cohen et al. 2017), which mainly formed from the combustion of fossil fuels in industrial, transport, and social sectors (Seinfeld and Pandis 2016). Several policies and measures have been made and implemented to improve the atmospheric environment over the past several decades; however, the air pollution level has never been within the acceptable range of WHO Air Quality standards in the region.

After COVID-19 was declared as a global pandemic (Ferretti et al. 2020; Givi et al. 2020; Mittal et al. 2020; Organization, 2020; Rana et al. 2020; Sohrabi et al. 2020), the countries around the globe started following the precautionary measures, including the implementation of the strict lockdown. Under lockdown, the main human activities, e.g. industrial manufacturing, educational, transportation, cultural, and trade, were restricted worldwide to prevent the further spread of COVID-19 (Chauhan and Singh 2020; Narayanan and Saha 2020; Pai et al. 2020). It is an absolute fact that the lockdown affected the socioeconomics negatively around the globe (ESA 2020; Öcal et al. 2020); however, its positive impacts on reduction in atmospheric NO₂ (Muhammad et al. 2020; Wright 2020) and water quality have been identified worldwide (Mishra et al. 2020; Öcal et al. 2020; Yunus et al. 2020). Our study hypothesized that overall Nitrogen (N) loading
from atmospheric deposition has significantly reduced during the COVID-19 forced lockdown, which, in turn, may improve river and coastal water quality and reduce the phytoplankton biomass (Garg et al. 2020; Mishra et al. 2020). Nitrogen loading to coastal aquatic ecology mainly arises from coastal upwelling, urban nutrients, atmospheric deposition, and agricultural practices (Paerl 1995; Ramesh et al. 2017; Voss et al. 2013). However, among these sources, N loading from atmospheric deposition mainly contributed to coastal water pollution by 40% (Ramesh et al. 2017; USEPA 1999). Therefore, it is critical to investigate the relationship between coastal water quality and nitrogen emission during COVID-19 forced confinement. During this period, the restricted social and economic activities on land might reduce N transport to coastal regions due to reduced NO2 emissions. There might be a connection between the reduced NO2 emissions and pollution in coastal regions. Mishra et al. (2020) described that the variations in bioavailable N loadings affect coastal regions’ pollution levels. In coastal waters, chlorophyll-a (chl-a) is a proxy to represent the phytoplankton biomass. Smaller values of chl-a would indicate a reduced pollution level in coastal regions. It is hypothesized that lockdown measures in South Asia may affect the N loadings through atmospheric deposition and watershed fluxes; thus, water pollution levels decline over coastal regions. It is necessary to investigate the links between NO2 emissions and chl-a through the relationships between surface runoff and N loadings to explore air and water pollution interactions. This issue has not been addressed appropriately in the previous research studies conducted during South Asia’s strict lockdown period. The quantitative assessments of exchange between air-water pollution under lockdown situations would help understand the effectiveness of reduced consumption of fossil fuels. Such investigation may also be useful for policymakers and local authorities to implement the environmental legislation for controlling pollution with minimum effects on socioeconomics.

The current study attempted to (a) quantitatively investigate the changes in the atmosphere pollution in two major South Asian countries (i.e. Pakistan and India) during COVID-19 lockdown and (b) investigate the effects of restricted human and industrial activities on the coastal water quality, and (c) identify the possible linkage between air and water pollution, addressing the exchange in pollutants along the coastal regions. The effects of restricted human and industrial activities on the atmospheric environment were explored based on the changes in NO2 emissions and Aerosol Optical Depth (AOD). The impacts of strict restrictions and changes in atmospheric pollutants on the hydrosphere were investigated based on (a) surface runoff changes over South Asia and (b) the changes in chlorophyll (Chl-a) concentration and turbidity along the coastal regions of the Indian Ocean with the Arabian Sea and Bay of Bengal. A multivariate statistical technique was used to explore the relationships among the human mobility changes on NO2 emissions and AOD.

Materials and methods

Description of the study area

Two major South Asian countries, i.e. Pakistan and India, were selected for analysis in the current study (Figure 1). Several major cities, including Karachi (PAK), Lahore, (PAK), Peshawar (PAK), New Delhi (IND), Ahmadabad (IND), Mumbai
(IND), Pune (IND), Hyderabad (IND), and Chennai (IND), were shortlisted to investigate the improvements in the atmospheric environment during the COVID-19 lockdown period at the city scale. Figure 1 describes the geographical location of the study region. The spread of COVID-19 started after mid-March in India and Pakistan, while only a few cases were detected at that moment. However, it spread very fast after 1st Apr, and Government authorities in both countries declared strict lockdown for citizens and prohibited most of the human, transport, and manufacturing activities to curb the COVID-19 spread.

**Data and methods**

Tropospheric NO$_2$ emissions and Aerosol Optical Depth (AOD) were acquired from remote sensing tools, i.e. Ozone Monitoring Instrument (OMI) and Moderate Resolution Imaging Spectroradiometer (MODIS). OMI onboard the NASA Aura satellite provides the NO$_2$ column density, and data is available from Oct 2004 to the present. In this study, daily average tropospheric NO$_2$ (OMNO2d.003) data was used because of improved sensitivity and algorithms of OMI for NO$_2$ detection at the lower atmosphere. The tropospheric NO$_2$ columns are retrieved from satellite observations based on the Differential Optical Absorption Spectroscopy (DOAS) technique within 405–465 nm (van Geffen et al. 2020). Moreover, a detailed description of the DOAS analysis and algorithm, data filtering, and quality control methods is available.
at https://earthdata.nasa.gov/. Similarly, MODIS aboard NASA Terra and Aqua satellites provide data to monitor aerosol optical depth and size distribution of the ambient aerosol. In the current research work, the latest record of daily AOD at 550 nm (MOD08_D3) was acquired at a resolution of 1° × 1° (Platnick et al. 2015). The monthly chlorophyll concentration (Chl-a) data were collected from MODIS-Aqua Level-3 products provided by OBPG (The NASA Ocean Biology Processing Group) at 4-km resolution from the NASA ocean color website (http://oceancolor.gsfc.nasa.gov/). Daily data of MODIS land surface reflectance band-1 of MOD09GQ product at a spatial resolution of 250 m × 250m was collected from the Land Processes Distributed Active Archive Center (LP DAAC) for the year 2019 and 2020.

Daily tropospheric NO2 and AOD data over Pakistan and India were analyzed using the Giovanni application of NASA (https://giovanni.gsfc.nasa.gov/giovanni/). NO2 and AOD maps were drawn from daily gridded data (Mar–May) averaged over the past five years (2015–2019) and compared with 2020 (i.e. before and after the lockdown). Anomaly changes in tropospheric NO2 and AOD were also computed. In order to investigate the tropospheric NO2 variations over the major cities, tropospheric NO2 time-series plotted based on the 15-days average over the 1° × 1° grid box drawn around the cities. Moreover, monthly maps of chlorophyll-a concentration and turbidity were also estimated for the Indian Ocean coastal regions to investigate the changes in Chl-a levels, a proxy for coastal water quality, phytoplankton densities, and algal blooms. We used the semi-analytic sediment model (SASM) to derive the coastal water quality in terms of turbidity, which had already been applied to MODIS Aqua observations (Dorji et al. 2016). Algorithms of the SASM model used in the present study are explained as following (Eq. (1))

\[
\text{Turbidity} = \frac{a \times \left( \frac{x}{1-x} \right)}{1 - b \times \left( \frac{x}{1-x} \right)}
\]

where \(x = \frac{a \times \sqrt{g_1^2 + 4 \times g_2 \times r_s}}{2 \times g_2}\). While \(g_1\) and \(g_2\) are the model’s constant parameters with values 0.0846 and 0.17, respectively, \(a\), \(b\), and \(c\) are the model calibrated parameters derived using regression analysis between in-situ observations and \(x\). \(r_s\) is calculated from surface reflectance data of MODIS onboard Aqua sensor calculated as \(r_s = \frac{R_s}{0.52 + 1.7 \times R_s}\). Due to the lack of ground observation data of coastal water quality, we used already calibrated model parameters values of \(a\), \(b\), and \(c\) from the study conducted by Yang et al. (2020).

The monthly surface precipitation (MERRA-2 Model M2TMNXFLX v5.12.4) and land surface runoff (MERRA-2 Model M2TMNXLND v5.12.4) at a spatial resolution of 0.5° × 0.625° were collected during 2000–2020. The variations in monthly surface precipitation and land-runoff were analyzed to eliminate land-based nitrogen loading effects, influencing the Chl-a concentration in coastal regions (Mishra et al. 2020).

The mobility trends of different human activities were extracted from Google during Feb–Oct 2020, to investigate the changes in anthropogenic activities. Geospatial statistical correlation between AOD and NO2 was also analyzed in ArcGIS to understand their mutual relationship.
Statistical analysis

The Principal Component Analysis (PCA) was used to investigate the relationships among the changes in human mobility indices at different places, NO$_2$, and AOD. PCA is a multivariate technique, which analyzes the data containing several inter-correlated quantitative dependent variables. It extracts the important information from data and represents it using orthogonal variables known as principal components.

Results and discussion

COVID-19 outbreak and human mobility

The daily time series of COVID-19 cases, number of deaths, recovered patients, and the mobility index of different human activities in Pakistan and India, are shown in Figure 2. All activities, including industries, educational sectors, shopping malls, social places, and transport, were running as usual until 27th Mar 2020. However, after the situation had gotten worse, government authorities in both countries declared strict lockdown for citizens, and stopped almost all anthropogenic activities to minimize the fast transmission of the COVID-19. The mobility index data of different human activities (Retail/recreations, grocery/pharmacy, workplaces, and transit stations) clearly indicated that the mobility trend was reduced by 80–90% in India and 60–70% in Pakistan. In comparison, the trend in residential areas was increased by 30–35% and 25–28% in India and Pakistan (Figure 2b).
Atmospheric NO$_2$ changes over South Asia

Under strict lockdown, energy consumption and power generation dropped substantially, which significantly lowered fossil fuel demand. Lesser use of fossil fuels consequently posed significant positive impacts on the environment. Similar inferences were drawn in the previous studies, e.g. Malik et al. (2020), Chauhan and Singh (2020), and Garg et al. (2020). Figure 3(a) illustrates the variations in monthly NO$_2$ emissions during the 2020 lockdown against the average of the last five years.

**Atmospheric NO$_2$ changes over South Asia**

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It was found that NO₂ emissions were much higher in Mar 2020, over the East Indian region ($15 \times 10^{15}$ molecules/cm²) comparative to the baseline period. However, NO₂ levels were reduced significantly during the lockdown period over most of the study region, especially during Apr–May 2020, compared to that in the baseline period 2015–2019 (Apr–May). Moreover, it was observed that the running mean of NO₂ value from 1st Jan to 20th Mar 2020 (before lockdown) coincided in fluctuation trends with the average time series of 2015–2019. While during strict lockdown (20th Mar to 30th July 2020), the time series of mean NO₂ emission over Pakistan and India moved with a lower running mean value than 2015–2019. From Figure 3(b), it is also evident that anomaly changes in NO₂ emission during Jan–Mar 2020 (before lockdown) have shown a positive trend indicating the high emissions from industrial and transport activities compared to the past years.

In contrast, anomaly changes in NO₂ emission during Mar–Jul 2020 (after lockdown) showed a negative trend after strict lockdown measures due to reduced industrial and transport emissions. New satellite images released by the European Union Copernicus program from the Copernicus Sentinel-5P satellite, also revealed that NO₂ emission had dropped by 40–50% during Mar–Apr 2020 compared to the same time-window for last year over Pakistan and India (ESA 2020). Several researchers have found that recent air quality improvements are linked to the less use of fossil fuels during strict lockdown measures adopted across the countries (Chauhan and Singh 2020; Dumka et al. 2021; ESA 2020; Kumar 2020; Wang and Su 2020). Sharma et al. (2020) and Singh and Chauhan (2020) also reported that NO₂ emissions have dropped over the India during Mar–Apr 2020 compared to the average of past years due to restricted anthropogenic activities. Air Quality Space Observation Laboratory from NASA reported that the power generation in South Asia has reduced by 10–25% during the lockdown (NASA 2020). The updated pieces of evidence from NASA, European Space Agency (ESA), and other researches have stated that air pollution has significantly been reduced over the metropolitan and industrialized regions (ESA 2020; Nakada and Urban 2020; NASA 2020) due to the strict lockdown measures.

Table 1 presents percent changes in NO₂ level over major cities during different lockdown scenarios. The negative values represent the level of NO₂ emissions dropped in 2020 compared to the past years (2015–2019). For example, maximum

| Country | City | Before lockdown Jan–Mar | Strict-lockdown Apr–Jun | Loosening lockdown Jul–Sep | Second wave Oct–Nov |
|---------|------|-------------------------|-------------------------|---------------------------|---------------------|
| India   | New Delhi | 10.90                   | –30.88                  | –8.52                     | –22.28              |
|         | Ahmadabad | 2.61                    | –19.89                  | 12.64                     | –21.88              |
|         | Chennai   | 3.76                    | –28.74                  | –2.88                     | –30.48              |
|         | Mumbai    | –1.33                   | –17.17                  | 5.19                      | –18.85              |
|         | Hyderabad | –0.68                   | –23.36                  | 2.49                      | –21.91              |
|         | Pune      | 2.05                    | –24.35                  | –3.92                     | –15.69              |
| Pakistan| Lahore    | 1.12                    | –31.75                  | –2.26                     | –21.92              |
|         | Karachi   | 7.90                    | –28.4                   | –2.10                     | –16.40              |
|         | Peshawar  | 6.21                    | –7.75                   | –3.88                     | –3.88               |
reductions in NO₂ emissions were noticed as 31%, 20%, 29%, 17%, 23%, 24%, 32%, 28%, and 8% over New Delhi, Ahmadabad, Chennai, Mumbai, Hyderabad, Pune, Lahore, Karachi, and Peshawar respectively during the strict lockdown period from Apr–Jun 2020. Similar to our findings, new data from the Copernicus Sentinel-5P satellite also revealed a 40–50% reduction in NO₂ emissions over major cities across India (ESA 2020). Figure 4 illustrates the time series extracted over the 1°×1° grid box drawn around the cities and indicates a 15-day moving average of NO₂ emission and anomaly changes in 2020 compared to the baseline average 2015–2019. Evidence from these results demonstrated that before the lockdown (1st Jan–15th Mar), a running mean and anomaly time series was coinciding with the average of 2015–2019 with a fluctuating trend. However, during the lockdown (15th Mar to Jul), mean NO₂ and anomaly values were dropped and running with lower values than the average of 2015–2019. It was also observed that after loosening lockdown (from Jul–Sep 2020), the NO₂ emission has jumped back to the past year average value and increased over some cities such as Ahmadabad, Mumbai, and Hyderabad. After the COVID-19 second wave that probably started in both countries after Oct 2020, the NO₂ emission level over some cities (Lahore, Mumbai, and New Delhi) has declined again compared to the average of past years (2015–2019) in the same months.

It was seen that during the first ten weeks of 2020, the NO₂ emissions were increasing compared to the past several years due to more industrial development and more emissions from transportation. After the 10th week of 2020, the NO₂ level started declining and reached the lowest value of the past five years’ average. Mahato et al. (2020) also reported that the level of NO₂ has dramatically slowed down just

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**Figure 4.** Time series of a 15-day moving average of NO₂ emission and anomaly changes in 2020 compared to the baseline period (2015–2019) across the selected major cities in Pakistan and India. Lime, orange, and light-yellow colors represent the ‘before lockdown’, ‘strict lockdown’, and ‘loosening lockdown’ stages in 2020.
within a few days due to the restricted anthropogenic activities during the lockdown period across India’s major cities. Some scientists reported that due to a decline in air pollution level, the sky over the most polluted city (e.g. New Delhi) was clearly visible than before. Restricted use of fossil fuels in transportation and the industrial sectors during the lockdown has significantly improved the air quality from ~30–54% over major cities in South Asia (Chauhan and Singh 2020; Mahato et al. 2020; Singh and Chauhan 2020). The average drop in NO2 emissions over the major cities such as Mumbai, Pune, and Ahmedabad was 40–49% during March 2020 (during the lockdown) compared with March 2019, which is consistent with the fewer emissions of effluents due to the shutdown of industrial activities.

**Airborne aerosol optical depth (AOD) over South Asia**

The atmospheric processes are significantly influenced and might be described by aerosols because of their direct effect on radiative balance (Barreto et al. 2020; Chylek and Wong 1995) and indirect effect (modification of cloud properties) (Charlson et al. 1992; Kim et al. 2014). Every year, enormous quantities of aerosols are released from human-induced sources and contribute to unhealthy levels of air pollution in major cities in South Asia (Murari et al. 2015; Sarkar et al. 2018). A higher value of aerosols optical depth of 1 or above indicates very hazy conditions. In contrast, its value less than 0.1 over the entire atmospheric vertical column is considered ‘clean’.
In this study, daily and monthly time series of AOD were retrieved from the MODIS on NASA Terra satellite, then processed through NASA Giovanni user interface from 1st Jan to 30th Oct 2020, and finally compared it with the average of last five years (2015–2019). Spatial changes in AOD during Feb–May 2020 were investigated and compared with the average of the past five years average (2015–2019) over South Asia (Figure 5a). AOD behaved differently in different countries during the lockdown periods, though NO$_2$ showed a consistent reduction (Nichol et al. 2020; Ranjan et al. 2020). AOD was noted much higher over India than Pakistan, which can be explained by the higher level of transport emissions and climate variations. Increasing trends of aerosols have been recorded in the past, attributed to the increased anthropogenic activities in terms of fossil and biofuel combustions and resultant emissions (Acharya and Sreekesh 2013; Jing and Singh 2020). It was noted that the average monthly AOD during Feb–Mar 2020 was mostly consistent with the average of the baseline period (2015–2019) during the same time window. However, the mean AOD during Apr–May 2020 was significantly reduced compared with the baseline (2015–2019). Reduction in AOD was correlated with the lockdown due to less emission of particles (such as NO$_x$ and SO$_x$) from human-induced activities. Simultaneously, a massive reduction in AOD (45%) was observed over the northern region of South Asia in Apr 2020. The time series of daily aerosol optical (AOD$_{550nm}$) averaged over South Asia is shown in Figure 5(b). It can be seen that the AOD level was increasing during the first 11 weeks of 2020 compared to the baseline period, while after the 11th week (during the lockdown), it started declining and reached the lowest observation on the date in MODIS record, due to less emission of particles from anthropogenic sources. However, after loosening lockdown (from July-Sep), the AOD level has jumped back to the previous level (2015–2019) due to reactivation in anthropogenic activities in both countries.

Scientists at NASA claimed a massive reduction in aerosol over South Asia during Mar–Apr 2020, compared with the same time-frame of the past years (NASA 2020). According to the scientists at NASA, aerosol particle depth in the northern plain was recorded the lowest in April, compared to the past 20 years observations of MODIS. It has been analyzed and presented that most aerosols formed in South Asia are linked to the emissions from anthropogenic sources, such as coal power plants, transportation, industries, and burning in agriculture farms (Guo et al. 2017; Jing and Singh 2020; Sarkar et al. 2018). Meanwhile, restricted use of fossil fuels in transportation and industrial sectors during the lockdown has decreased the emissions sources of airborne particles in the atmosphere; therefore, air pollution across the countries have drastically slowed down just within a few days (Chauhan and Singh 2020; Isaifan 2020; Sharma et al. 2020). The reduced aerosols might also be beneficial in several aspects, including a reduction in transmission of airborne diseases (Li et al. 2020), improved human health, and a positive impact on vegetation growth (by lesser deposition on leaves) (Wang et al. 2020).

**Impacts of human mobility on changes in AOD and NO$_2$**

Geospatial statistical correlation between the daily changes in AOD and NO$_2$ was investigated to analyze the possible relationship between both variables. Figure 6
shows the spatial correlation between AOD and NO₂ and the correlation circle based on PCA. It was noticed that in most of the regions, the spatial correlation remained positive (0.23–0.50), indicating that a reduction in NO₂ might explain the decrease in AOD. Figure 6(b) represents 94% information of inter-correlations among the variables, while the principal component F1 contains 85% information. It is evident from Figure 6(b) and Table 2 that variations in the human mobility have significant impacts on the NO₂ emissions and AOD in South Asia. Human mobility was significantly reduced at all the places except residential, where it was increased due to stay at home orders during the lockdown. The reduction in NO₂ emissions and AOD had significantly positive correlations (Table 2) with the reductions in human mobility at workplaces, parks, transit stations, groceries, pharmacies, retailers, and recreational places. The mobility index in residential areas was negatively correlated with the mobility indices at all other places. Meanwhile, the mobility index in residential areas was significantly negatively correlated with reducing NO₂ emissions and AOD (Figure 6b). During the lockdown period, the movement of people was restricted; therefore, the use of transportation was reduced enormously. Industries and other workplaces were also not in working conditions, which resulted in lesser fossil fuel consumption. Resultantly, NO₂ emissions and AOD were reduced significantly. This whole scenario highlights that the lockdown has affected the environment positively.

Coastal aquatic ecology along the Indian Ocean

The aquatic ecology, as a proxy of coastal water quality, phytoplankton densities and algal blooms, was investigated using changes in chlorophyll (Chl-a) and turbidity along the coastal regions of the Indian Ocean. Figure 7 depicts the monthly comparison of Chl-a in 2020 and baseline (2019) along the coastal regions in the Indian Ocean. Evidence from this study depicted that during the strict lockdown period,
Chl-a concentration has substantially declined along the coastal regions of the Indian Ocean, especially over three target regions (1) coastal regions of Pakistan in the Arabian sea, (2) west-coastal regions of India, and (3) coastal regions of India in the Bay of Bengal. Chl-a concentration along the coastal regions of Pakistan was much higher before and during the pre-lockdown stage in 2020 and was highly comparable to the past year’s average with slight variations. However, after the strict lockdown was imposed in both countries, a considerable decline in Chl-a concentration could be seen over all the coastal regions. The changes are much visible along the coastal regions of Pakistan. It could be seen that during the lockdown period, the average concentration of Chl-a along the coastal regions of Pakistan and west-coastal regions of India was approximately greater than 10 mg/m³; however, after strict lockdown, its concentration has reduced to less than 5 mg/m³, which shows 50% decline in coastal Chl-a concentration.

The concentration of Chl-a has been reported higher in winter (Oct–Dec) than summer (Jun–Sep) in the region. Although, the relationship between the sea surface temperature and Chl-a is significant (Dunstan et al. 2018), the variations in N loadings affect the concentration of Chl-a (Kumar et al. 2016). The N loadings and movement of deeper water to the surface cause cooling events and enhance the Chl-a concentration. The cooling events are favorable for the increase of Chl-a concentration. Due to the lockdown, lesser N loadings were transferred to the coastal areas, and thus, Chl-a concentrations were identified as lesser than previous years (Figures 7 and 8). The phytoplankton biomass reduction findings are in line with the study of Mishra et al. (2020). Figure 8 illustrates the mean monthly comparison of Chl-a concentration before and after the lockdown period in 2020 and 2019 over three different coastal regions in the Indian Ocean.

Moreover, we also investigated the changes in coastal water turbidity along the three main coastal regions such as (1) Karachi along the west coastal region of Pakistan, (2) Mumbai along the west coastal region of India, and (3) Madras, Dhaka, and Calcutta along the east coastal region of India in the Indian Ocean. Figure 9(a)–(e) represents the time series variations in the 15-days moving average of turbidity (NTU) in 2020 compared to 2019 in different lockdown scenarios over coastal regions. It can be seen that turbidity along the coastal areas of Karachi, Calcutta, and Dhaka has clearly declined during the lockdown period (Apr–Jul) in 2020 compared to 2019; however, turbidity at Madras is still increasing. It was observed that during

| Variables     | R&R   | G&P   | Parks  | Workplaces | Residential | TS   | NO2  | AOD  |
|---------------|-------|-------|--------|------------|-------------|------|------|------|
| R&R           | 1.00* |       |        |            |              |      |      |      |
| G&P           | 0.86* | 1.00* |        |            |              |      |      |      |
| Parks         | 0.99* | 0.88* | 1.00*  |            |              |      |      |      |
| Workplaces    | 0.94* | 0.97* | 0.95*  | 1.00*      |              |      |      |      |
| Residential   | −0.98*| −0.94*| −0.98* | −0.99*     | 1.00*        |      |      |      |
| TS            | 0.98* | 0.95* | 0.99*  | 0.99*      | −0.99*       | 1.00*|      |      |
| NO2           | 0.72* | 0.66* | 0.77*  | 0.71*      | −0.74*       | 0.73*| 1.00*|      |
| AOD           | 0.69* | 0.39  | 0.65*  | 0.55*      | −0.62*       | 0.58*| 0.52*| 1.00*|

G&P = groceries and pharmacies, TS = transit stations, R&R = retailers and recreational places.
*level of significance = 0.05

Table 2. Correlations among the human mobility indices and atmospheric pollution variables (NO2 and AOD).
strict lockdown, the turbidity has decreased by 29%, 11%, 16%, and 17% along the coastal regions of Karachi, Mumbai, Calcutta, and Dhaka, respectively, while a 5–6% increase in turbidity was seen over the Madras during the same period (Figure 9f). The current noticeable changes in Chl-a concentration and turbidity might be due to the combined effects of reduced urban nutrient pollutants and less deposition of atmospheric nitrogen (N) to the coastal regions during COVID-19 forced confinement (Mishra et al. 2020). Previous studies have also demonstrated that nitrogen
dioxide ($\text{NO}_2$) generated from anthropogenic emissions such as industries, urban transports, air traffics, urban wastes, and agricultural activities play a critical role in affecting coastal water quality (Paerl et al. 2002; Stevens et al. 2018). This research does not collect the field data to investigate the effects of these pollutants directly. Meanwhile, we used an indirect approach by investigating the land-surface runoff, as a proxy of nutrients loading to coastal regions during the study period.

Figure 8. Mean monthly comparison of Chl-a concentration before and after the lockdown period in 2020 and 2019 over three different coastal regions in the Indian Ocean.

Figure 9. Time-series variations in 15-days moving average of turbidity in 2020 compared to 2019 in different lockdown scenarios over coastal regions of the Indian Ocean.
Figure 10 shows a comparison of overland runoff over the study region during 2019 and 2020 in different lockdown periods. Images displayed in column-1 and column-2 indicate the monthly runoff for 2019 and 2020, respectively. The 3rd column indicates the time-series changes in monthly surface precipitation and overland runoff from 2002–2020. Red and blue rectangle drawn on time series of surface precipitation and runoff graph indicate the observations in 2019 and 2020, respectively.

Figure 10 shows a comparison of overland runoff over the study region during 2019 and 2020 in different lockdown periods at a monthly scale to investigate the anomalous events, which could affect the N loading to coastal regions. Besides, we also addressed the past 20 years’ variations in surface runoff and precipitation, as shown in Figure 10. The amount of surface precipitation and runoff in western Pakistan and Eastern Bengal were higher in 2020 than in 2019. On the other hand, in India’s central region, both parameters are highly comparable to past years without significant variations. This phenomenon counterweights and eliminates the effects of land-based nutrients load on coastal regions and shows that the observed decline in Chl-a concentration and turbidity in India’s west coastal region might be the reason
for the reduced atmospheric deposition of nitrogen. Besides, Pakistan’s coastal region received higher land surface runoff due to higher precipitation and, hence, a high amount of land-based nutrients to the coastal region. However, during the lockdown period, the Chl-a concentration and turbidity decreased by 40–50% and 30–37%, respectively.

It is possibly interlinked to the reduced atmospheric deposition of nitrogen. Mishra et al. (2020) also reported that even though a higher amount of land-based runoff was received in the coastal region in the Bay of Bengal during pre-monsoon (Apr–May), but the Chl-a concentration has reduced by 30% during this period. It was also seen that western coastal regions along the Pakistan and India showed a higher reduction in Chl-a than eastern coastal regions. This might be because Western coastal regions are heavily urbanized, and sudden and forced confinement during COVID-19 substantially reduced the atmospheric nitrogen (Singh and Chauhan 2020), affecting the coastal water quality (Mishra et al. 2020). Additionally, agriculture activities were running normally during the lockdown period as before, so these hypotheses address that coastal regions have experienced a higher decline in phytoplankton biomass due to reduced atmospheric N deposition, which improves the coastal water qualities.

**Conclusion**

The strict lockdown measures across the globe did not only control the spread of the COVID-19 virus, but also has positively affected the environment. The hypothesis of the study got proven that restricted human mobility, transportation, and industrial activities significantly reduced the air pollution. Besides, the changes in air pollution, due to declined NO2 emissions, also affected the coastal water pollution. A significant reduction in air and water pollution was observed in South Asia due to the restricted human activities since mid-Mar 2020. The analysis of remote sensing data and local factors during the lockdown compared to the last five years (2015–2019) helped understand the potential salutary effects of the restricted anthropogenic activities on the environment (~30–40% and 45% reduction in NO2 emissions and AOD, respectively). A significant positive correlation between AOD and NO2 suggests that changes in AOD may be related to a reduction in trace gasses. The findings of the current research work provided evidence that the reductions in AOD and NO2 emissions are associated with the lesser consumption of fossil fuels. Moreover, water quality along the coastal regions of South Asian cities also improved due to reduced nitrogen emission during the strict lockdown period, which depicted that the air and water pollutions are strongly interconnected. An improvement in air quality would help improve the water quality. It is recommended that local governments worldwide implement such strict universal restrictions on fossil fuel consumption and mass transportation for a specific period (e.g. 15–30 days) every year to heal the Earth’s environment.

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**Author contributions**

Dr. Muhammad Shafeeque and Mr. Arfan Arshad conceived ideas to carry out this research under Dr. Quoc Bao Pham’s guidance. Mr. Arfan Arshad and Dr. Muhammad Shafeeque performed the experiments, analyzed the results, and drafted the manuscript. Dr. Quoc Bao Pham, Dr. Nadhir Al-Ansari, Dr. Muhammad Shafeeque, Dr. Abid Sarwar, Ahmed Elbeltagi, Dr. Shahbaz Nasir Khan and Mr. Adil Dilawar provided help in reviewing the manuscript, English editing, and modified the manuscript.

**Disclosure statement**

The authors declare no conflict of interest.

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