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The effect of COVID-19 pandemic on human mobility and ambient air quality around the world: A systematic review

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Abstract

We conducted this systematic review to identify and appraise studies investigating the coronavirus disease 2019 (COVID-19) effect on ambient air pollution status worldwide. The review of studies was conducted using determined search terms via three major electronic databases (PubMed, Web of Science, and Scopus) according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. A total of 26 full-text studies were included in our analysis. The lockdown measures related to COVID-19 pandemic caused significant decreases in the concentrations of PM$_{2.5}$, NO$_2$, PM$_{10}$, SO$_2$ and CO globally in the range of 2.9%–76.5%, 18.0%–96.0%, 6.0%–75.0%, 6.8%–49.0% and 6.2%–64.8%, respectively. However, O$_3$ concentration increased in the range of 2.4%–252.3%. The highest decrease of PM$_{2.5}$ was found in 16 states of Malaysia (76.5%), followed by Zaragoza (Spain) with 58.0% and Delhi (India) with 53.1%. The highest reduction of NO$_2$ was found in Salé city (Morocco) with 96.0%, followed by Mumbai (India) with 75.0%, India with 70.0%, Valencia (Spain) with 69.0%, and São Paulo (Brazil) with 68.0%, respectively. The highest increase of O$_3$ was recorded for Milan (Italy) with 252.3% and 169.9% during the first and third phases of lockdown measures, and for Kolkata (India) with 87% at the second phase of lockdown measures. Owing to the lockdown restrictions in the studied countries and cities, driving and public transit as a proxy of human mobilities and the factors affecting emission sources of ambient air pollution decreased in the ranges of 30–88% and 45–94%, respectively. There was a considerable variation in the reduction of ambient air pollutants in the countries and cities as the degree of lockdown measures had varied there. Our results illustrated that the COVID-19 pandemic had provided lessons and extra motivations for comprehensive implementing policies to reduce air pollution and its health effects in the future.

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1. Introduction

The coronavirus disease 2019 (COVID-19) caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has emerged in Wuhan, China (Dacre et al., 2020; Niazi et al., 2020; Rugani and Caro, 2020), triggering a significant challenge for communities, healthcare organizations and economies worldwide (Faridi et al., 2020; Petroni et al., 2020). Consequently, most countries across the world implemented lockdowns or quarantine/isolation measures to slow down the spread of the virus (Bao and Zhang, 2020; Gautam, 2020b; Sicard et al., 2020). As a consequence of these implementations, there were direct/indirect significant changes in the economic and environmental statuses (Dacre et al., 2020; Faridi et al., 2020c; Gautam, 2020a; Mahato et al., 2020). The COVID-19 pandemic has halted all human being’s socio-economic activities, thereby the global oil demand plunged and as a result prices cut down sharply (Chauhan and Singh, 2020; Muhammad et al., 2020). Contrary to negative dramatic economic impacts due to SARS-CoV-2 spread (Agrawala et al., 2020; Collivignarelli et al., 2020; Dantas et al., 2020; Wang and Su, 2020), a considerable improvement in ambient air quality status was observed globally, particularly in the heavily polluted countries/cities (Agrawala et al., 2020; Dutheil et al., 2020; Gautam, 2020a; Lancet, 2020; Zambrano-Monserrate et al., 2020). The association between COVID-19 pandemic and ambient air quality status has been studied via various data analysis methodologies in different countries/cities. Therefore, it is fundamentally essential to combine and compare the results of these studies to support national and international policy-makers for adopting the most effective air pollution measures in the future. The present study aimed to summarize and assess the existing research findings of the impacts of the COVID-19 pandemic on air quality status globally. We also included the changes in meteorological parameters reported by conducted studies and human mobility index data to show

![Fig. 1. PRISMA flow diagram for selection of relevant studies.](image-url)
significant ambient air quality status changes during the lockdown measures.

2. Methods

2.1. Search strategy and criteria for studies selection

This systematic review aimed to review the studies investigating the relationship between SARS-CoV-2 and the status of ambient air quality worldwide. We explored the relevant studies published in three primary electronic databases of Scopus, Web of sciences, and PubMed from 1st January 2020 until 30th May 2020. The search strategy was developed using the following keywords: “Coronavirus”, “Corona”, “COVID”, “2019-nCoV acute respiratory disease”, “Novel coronavirus pneumonia”, “Severe pneumonia with novel pathogens”, “coronavirus 2”, “SARS-CoV-2”, “SARS virus”, “Covid pandemic”, “Covid lockdown”, “air quality”, “air pollution”, “environmental pollution”, “atmospheric pollution”, “air pollutants”, “particulate matter”, “PM2.5”, “PM10”, “NO2”, “NOx”, “nitrogen dioxide”, “nitrogen oxides”, “SO2”, “sulfur dioxide”, “carbon monoxide”, “CO”, “O3”, “ozone”, “tropospheric ozone”. Boolean operators such as “AND” and “OR” were used to combine the above-mentioned search key terms. Also, to increase the sensitivity and gather higher records (specifically for pre-proof manuscripts), additional documents were identified from hand-searching and reviewing the referenced list of retrieved papers. This systematic review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guideline (Fig. 1). Studies were included if they met the following criteria: 1) published in a peer-review journal in English, 2) reported the quantitative and qualitative data for the association between air quality and COVID-19 pandemic. We excluded preprints, non-English language papers, conference abstracts, news articles, and posters. Two of the authors reviewed the titles and abstracts separately and selected the relevant studies. The final included studies were based on the full-text evaluation.

3. Results

3.1. Search results

As shown in Fig. 1, the initial searches provided 934 records (Scopus: 403, PubMed: 382, and Web of sciences: 149 documents). Also, we identified four records through other sources. In the screening step, 884 articles were unrelated to the purpose of our study and were excluded based on the title and abstract, and duplication. Finally, the remaining 54 studies were reviewed for eligibility evaluation, which by the end, 26 full-text articles met the inclusion criteria for the extraction of their findings.

3.2. Description of included studies

Out of the 26 reviewed studies that met our quantitative and qualitative inclusion criteria, (Fig. S1) 15 were conducted in Asia (China, Malaysia, India, United Arab Emirates (UAE), Kazakhstan, Singapore, Thailand, Vietnam, Indonesia, Philippines, Cambodia, Table 1

| Activities                                      | Spain | Italy | France | USA | China | Malaysia | Brazil | India | UAE | Kazakhstan |
|-------------------------------------------------|-------|-------|--------|-----|-------|----------|--------|-------|-----|------------|
| Public Transportation                           |       |       |        |     |       |          |        |       |     |            |
| Religious Places                                |       |       |        |     |       |          |        |       |     |            |
| School/Universities                             |       |       |        |     |       |          |        |       |     |            |
| Movements (Traveling between states and abroad) |       |       |        |     |       |          |        |       |     |            |
| Closing Businesses                              |       |       |        |     |       |          |        |       |     |            |
| Shopping Centers except for essential services  |       |       |        |     |       |          |        |       |     |            |
| Industrial Activates except for essential industries |     |       |        |     |       |          |        |       |     |            |
| Social contact (Parks, Beaches, Restaurants, etc.) | |       |        |     |       |          |        |       |     |            |

Table 1: Scheme of activities allowed and prohibited during COVID-19 lockdown in the included studies.

In other countries (Singapore, Thailand, Vietnam, Indonesia, Philippine, Cambodia, Laos, Myanmar, and Morocco), lockdown measures without reporting any types of activities were reported.
PM$_{2.5}$ changes due to COVID-19 lockdown (%)

- Malaysia, Klang Valley
- Spain, Zaragoza I
- India, Delhi I
- China, Beijing II
- China, Shanghai I
- Italy, Milan III
- India, Bangalore II
- Italy, Rome III
- India, Delhi I
- India, 22 cities
- Malaysia, 16 states
- India, Delhi I
- Kazakhstan, Almaty
- India, Chennai II
- Italy, Milan
- China, Wuhan
- China, Wuhan, Jingmn, Enshi I
- India, Dehli I
- China, Yangtze River Delta
- India, Mumbai I
- India, Delhi II
- Malaysia
- USA, New York I
- China, Yangtze River Delta II
- China, Hubei Province
- China, Wuhan, Jingmn, Enshi II
- USA, Los Angeles II
- Brazil, Sao Paulo I
- India, Kolkata II
- Italy, Rome II
- India, Kolkata I
- India, Bangalore I
- Northern China, 366 urban areas
- USA, New York II
- Italy, Milan
- China, Wuhan, Jingmn, Enshi III
- China, 337 major cities
- India, Mumbai I
- India, Chennai I
- India, Turin
- Spain, Valencia
- China, Yangtze River Delta III
- UAE, Doha I
- UAE, Doha II
- USA, Los Angeles I
- Brazil, Sao Paulo II
- France, Nice
- Italy, Rome

Fig. 2. PM$_{2.5}$ changes (%) due to COVID-19 pandemic lockdown bans over the world.
Fig. 3. NO₂ changes (%) due to COVID-19 pandemic lockdown bans over the world.
Fig. 4. PM$_{10}$ changes (%) due to COVID-19 pandemic lockdown bans over the world.
Fig. 5. SO$_2$ changes (%) due to COVID-19 pandemic lockdown bans over the world.

| Countries/ Studies                          | SO$_2$ Changes due to COVID-19 Lockdown (%) |
|---------------------------------------------|---------------------------------------------|
| Morocco, Sale city                          | -50%                                        |
| China, Wuhan, Jingmn, Enshi I               | -40%                                        |
| China, Hubei Province                       | -30%                                        |
| China, Wuhan, Jingmn, Enshi II              | -20%                                        |
| Brazil, Sao Paulo I                         | -10%                                        |
| China, Wuhan, Jingmn, Enshi III             | 0%                                          |
| China, Yangtze River Delta I                | 10%                                         |
| China, Yangtze River Delta III              | 20%                                         |
| Italy, Milan II                             | 30%                                         |
| China, Yangtze River Delta II               | 40%                                         |
| Malaysia                                    | 50%                                         |
| Italy, Milan I                              | 60%                                         |
| India, Delhi                                | 70%                                         |
| India, 22 cities                            | 80%                                         |
| Kazakhstan, Almaty                          | 90%                                         |
| Brazil, Sao Paulo II                        | 100%                                        |

SO$_2$ changes due to COVID-19 pandemic lockdown bans over the world.
Fig. 6. CO changes (%) due to COVID-19 pandemic lockdown bans over the world.
Fig. 7. O₃ changes (%) due to COVID-19 pandemic lockdown bans over the world.
### Table 2
Detail information on the included studies investigating the effect of COVID-19 on ambient air quality status.

| Study ID | Country/Cities | Methodology | Sources of air quality data | Air pollutants | The changes of ambient air pollutants |
|----------|----------------|-------------|-----------------------------|----------------|--------------------------------------|
| Abdullah et al., 2020 | Malaysia (16 states) | Before MCO (14–17 March 2020) vs During Phase I MCO (18–31 March 2020) During Phase I vs Phase II MCO (1–14 April 2020) | SAQMSs² (68 stations: 1 background and 67 traffic and residential) | PM₂,₅ | O₃: +20.1 μg m⁻³ (+51.0) |
| Wang et al., 2020 | Northern China (30 Cities) | Before lockdown: 1 to 23 January 2020 & During lockdown: 24 January to 9 February 2020 | SAQMSs (366 sites: traffic, residential, industrial, and background) | AQI, PM₂,₅, PM₁₀, CO, SO₂, NO₂, and O₃ | O₃: +24.0 |
| Sicard et al., 2020 | Nice, Rome, Turin, Valencia, Wuhan | Between two time periods in 2020 and the same periods averaged over 2017–2019: Before lockdown (from 1st January until the start date of the lockdown) and During the lockdown (from the start date of the lockdown until 8th April in Wuhan i.e. the end date of the lockdown, and until 18th April in Nice, Turin, Rome, and Valencia). | SAQMSs (36 traffic, industrial and residential stations: 3 ones for Nice, 15 ones for Rome, 4 stations for Turin, 6 sites for Valencia, and 8 sites for Wuhan) | NO, NO₂, PM₁₀, PM₂,₅, PM₁₀, and O₃ | O₃: (+13.6), PM₁₀⁻: (+1.8), PM₂,₅⁻: (+10.6) |
| Siciliano et al., 2020 | Brazil (Rio de Janeiro) | Partial lockdown (03/23/2020–04/05/2020) vs Before the partial lockdown (03/01/2020–03/22/2020) Relaxed partial lockdown (04/06/2020–04/16/2020) vs Before the partial lockdown (03/01/2020–03/22/2020) | SAQMSs (2 stations: traffic and industrial) | NOₓ, O₃, and NMHC | O₃: (+6.3 to +12.9) NOₓ: (−24.4 to −81.1), NMHC: (−14.3 to −25.0) |
| Collivignarelli et al., 2020 | Italy, Milan | Phase I: Reference period (CTRL): February 7, 2020, to February 20, 2020, vs Partial Lockdown: 9th to 22nd of March 2020 Phase II: Reference period (CTRL): February 7, 2020, to February 20, 2020, vs Total Lockdown: 23rd of March to 5th of April, Phase III: Partial Lockdown: 9th to 22nd of March 2020 vs Total Lockdown: 23rd of March to 5th of April, | SAQMSs | PM₁₀, PM₂,₅, BC, PM₁₀, BC, Benzene, SO₂, CO, and NOₓ | O₃: (+169.9) PM₁₀⁻: (−39.5), PM₂,₅⁻: (−37.1), BC: (−57.5), Benzene: (−49.6), CO: (−45.6), SO₂: (−19.9), NOₓ: (−43.1), NO₂: (−59.9) |
| Dantas et al., 2020 | Brazil (Rio de Janeiro) | During the lockdown: March 2–15, 2020 (First and Second weeks) vs Third (03/16–03/22), Fourth (03/23–03/29) | SAQMSs (3 stations: industrial, traffic, and residential ones) | PM₁₀, NO₂, CO, O₃, and NMHC | PM₁₀⁻: Fifth week (+2.1 to +3.6), Sixth (+3.6 to +25.5), O₃: Third week (+31.1 to +63.0), Fourth week (~2.7 to (~63.0)) PM₁₀⁻: Third week (~15.1 to +10.7), Fourth week (~17.5 to ~33.5), NO₂: Third week (~1.8 to ~28.8), (continued on next page) |
| Study ID | Country/Cities | Methodology | Sources of air quality data | Air pollutants | The changes of ambient air pollutants |
|----------|----------------|-------------|----------------------------|----------------|--------------------------------------|
| Sharma and Zhang, 2020 | India (22 cities) | During lockdown: March 16th to April 14th from 2020 vs the same period of 2017, 2018 and 2019 | SAQMSs (30 stations without reporting their types) | AQI, PM10, PM2.5, CO, NOx, NO2, O3 and SO2 | O3: (+17.0) NGC: Fourth week (~32.2 to ~53.9), Fifth week (~19.7 to ~32.1), Sixth (~16.8 to ~1.4), CO: Third week (~15.2 to +12.0), Fourth week (~41.3 to ~48.5), Fifth week (~30.3 to ~30.4), Sixth week (~30.3 to ~42.4), NMHC: Fourth and Fifth weeks (~28.4 and ~14.3) |
| Burns et al., 2020 | China (Yangtze River Delta such as Shanghai, Hangzhou, Nanjing, Hefei with 41 cities) | Pre-lockdown: 1st January to 23rd January 2020 vs same periods in 2019 Level I: roughly 24th January to 25th February 2020 vs same periods in 2019 Level II: roughly 26th February to 31st March 2020 vs same periods in 2019 | SAQMSs (41 stations without reporting their types) | PM2.5 | O3: (+10.4) PM2.5: (~12.3), PM10: (~19.6), CO: (~7.8), NO2: (~18.5), SO2: (~29.3) |
| Chauhan and Singh, 2020 | UAE (Dubai) USA (New York) USA (Los Angeles) Spain (Zaragoza) Italy (Rome) | Phase I: March 2020 vs March 2019 (covered Chinese Spring Festival) Phase II: March 2020 vs February 2020, Phase III: February 2020 vs January 2020 | SAQMSs (NR) | PM2.5 | O3: (+20.5) PM2.5: (~13.8), PM10: (~33.7), CO: (~20.9), NO2: (~45.1), SO2: (~20.4) |
| Kree et al., 2020 | Brazil (São Paulo) | Before lockdown: March 2–20, During lockdown: March 24–April 3 | SAQMSs (13 stations without reporting their types) | NOx | – |
| Xu et al., 2020b | China (Hubei province) | Before lockdown: January to March 2017–2020: February 2017–2019, February 2020 | SAQMSs (NR) | PM2.5, PM10, CO, NO2, NOx, O3 and AQI | O3: (+14.3) PM2.5: (~30.1), PM10: (~40.5), SO2: (~4.0), CO: (~27.9), NO2: (~61.4) |
| Mahato et al., 2020 | India (Delhi) | Before lockdown: 2nd March to 21st March vs During lockdown: 25th March to 14th April 2020 24th March to 14th April during 2017 to 2020 | SAQMSs (34 stations: traffic, industrial and residential) | PM10, PM2.5, SO2, NO2, CO, O3, NH3, and AQI | O3: (+0.78) PM2.5: (~53.1), PM10: (~51.9), SO2: (~18.0), NO2: (~52.7), CO: (~30.4), NH3: (~12.3), AQI: (~61.0) |
| Xu et al., 2020a | China (Wuhan, Jingmen, Enshi) | January 2017–2019 vs 2020 | SAQMSs (NR) | PM10, PM2.5, SO2, NO2, CO, O3 and AQI | O3: (+12.7) PM2.5: (~37.6), PM10: (~36.2), SO2: (~45.0), NO2: (~35.6), CO: (~30.4) |

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Table 2 (continued)

| Study ID | Country/Cities | Methodology | Sources of air quality data | Air pollutants | The changes of ambient air pollutants |
|----------|----------------|-------------|-----------------------------|----------------|---------------------------------------|
|          |                |             |                             |                | Concentration (percent changes)       | Concentration (percent changes) |
|          |                |             |                             |                | (–28.8) and AQI: (–32.2)              | PM$_{2.5}$: (–40.5), PM$_{2.5}c$: (–30.1), SO$_2$: (–33.4), NO$_2$: (–61.4), CO: (–27.9) and AQI: (–27.7) |
|          |                |             |                             |                | O$_3$: (+14.3)                        | PM$_{2.5}$: (–45.0), PM$_{2.5}c$: (–52.0), NO$_2$: (–50.0), CO: (–29.0) |
|          |                |             |                             |                | O$_3$: (+11.6)                        | PM$_{2.5}$: (–45.0), PM$_{10}$: (–52.0), NO$_2$: (–48.0), CO: (–41.0), O$_3$: (–14.0) |
|          | India (Delhi)  | Phase I: March-April 2019 and March-April 2020 | SAQMSs (69 stations without reporting their types: 38 stations for Delhi, 10 ones for Mumbai, 4 ones for Chennai, 10 ones Bangalore, 7 ones for Kolkata) | PM$_{2.5}$, PM$_{10}$, CO, NO$_2$ and O$_3$ | O$_3$: (+7.0) | PM$_{2.5}$: (–33.0), PM$_{10}$: NR: (–47.0), NO$_2$: (–75.0), CO: (–46.0) |
|          | India (Mumbai) | Phase I: March-April 2019 and March-April 2020 |                             |                | O$_3$: (+8.0) | PM$_{2.5}$: (–32.0), CO: (–35.0) |
|          | India (Chennai) | Phase I: March-April 2019 and March-April 2020 |                             |                | O$_3$: (+3.0) | PM$_{2.5}$: (–14.0), PM$_{10}$: NR: (–34.0), NO$_2$: (–43.0), CO: (–23.0) |
|          | India (Bangalore) | Phase I: March-April 2019 and March-April 2020 |                             |                | O$_3$: (+73.0) | PM$_{2.5}$: (–22.0), PM$_{10}$: (–34.0), NO$_2$: (–60.0), CO: (–16.0), O$_3$: (–11.0) |
|          | India (Kolkata) | Phase I: March-April 2019 and March-April 2020 |                             |                | O$_3$: (+17.0) | PM$_{2.5}$: (–22.0), PM$_{10}$: (–34.0), NO$_2$: (–60.0), CO: (–29.0) |
|          | China (Wuhan)  | Phase I: March-April 2019 and March-April 2020 |                             |                | O$_3$: (+87.0) | PM$_{2.5}$: (–27.0), PM$_{10}$: (–32.0), NO$_2$: (–66.0), CO: (–16.0) |
|          | China (367 cities) | Before lockdown: from January 1st to 20th and After quarantines: from February 10th to 25th | Satellite data, NASA | NO$_2$, CO | NO$_2$: (–30.0), CO: (–25.0) |
|          | China (Wuhan)  | January 1, 2016 vs March 14, 2020 | Satellite data, Sentinel-5 | PM$_{2.5}$, NO$_2$ | NO$_2$: (–12.9) g/m$^3$, PM$_{2.5}$, (–18.9) g/m$^3$, NO$_2$: (–22.8) g/m$^3$, PM$_{2.5}$: (–1.4) g/m$^3$ |

(continued on next page)
| Study ID | Country/City | Methodology | Sources of air quality data | Air pollutants | The changes of ambient air pollutants |
|----------|--------------|-------------|-----------------------------|----------------|----------------------------------|
|          |              |             |                             |                | Concentration (percent changes) |
|          |              |             |                             |                | Concentration (percent changes) |
| (Gautam, 2020a) | India | Before and after COVID-19 (March 2019–March 2020) | Satellite data, Sentinel-5P | NO2 | (−30.0) |
| (Gautam, 2020a) | India | Before and after COVID-19 (March 2019–March 2020) | Sentinel-5P and Aura | NO2 | (−30.0) |
| (Muhammad et al., 2020) | China (Wuhan) | 2019. January, February 2020 | Satellite data, Sentinel-5P | NO2 | (−20.0 to −30.0) |
| (Muhammad et al., 2020) | China | Before and after lockdown January, February 2020 | Sentinel-5P and Aura | NO2 | (−20.0 to −30.0) |
| (Nakada and Urban, 2020) | Brazil (São Paulo) | Phase I: Five-year monthly (February, April, March 2015–2019) vs Four-week before partial lockdown (February 25, 2020, to March 23, 2020) | SAQMSs (4 stations: 3 traffic stations and one industrial) & Remote sensing (NO2) | PM2.5, PM10, CO, SO2, NO, NOx, NO2, and O3 | PM10 (−12.7 to −22.8), PM2.5 (−29.8), NO: (−77.3 to +8.1), NO2: (−5.6 to −54.3), NOx (−65.4 to +3.0), O3: (−4.3 to +31.5), SO2: (−18.1 to −32.7) and CO: (−36.1 to −64.8) |
| (Nakada and Urban, 2020) | Brazil (São Paulo) | Phase II: Five-year monthly mean (February, April, March 2015–2019) vs Four-week during partial lockdown (from March 24, 2020, to April 20, 2020) | SAQMSs (4 stations: 3 traffic stations and one industrial) & Remote sensing (NO2) | PM2.5, PM10, CO, SO2, NO, NOx, NO2, and O3 | PM10 (−6.2 to +21.4), O3 (−2.9 to +13.4), SO2 (−6.2 to +8.0) |
| (Tobias et al., 2020) | Spain (Barcelona) | Before lockdown: February 16th to March 13th, 2020 vs During lockdown: March 14th to 30th March 2020 | SAQMSs (2 stations: one traffic and another urban background) | PM10, NO2, O3, BC, SO2 (μg/m³) | O3: (+14.9 to +28.5) |
| (Tobias et al., 2020) | Spain (Barcelona) | Before lockdown > February 16th to March 13th, 2020 vs During lockdown: March 14th to 30th March 2020 and Phase II: During lockdown: March 14th to 30th March 2020 vs March 14th to 30th March 2019 | Remote sensing data, Copernicus Sentinel-5 | NO2 | PM10: −2.7 (−27.8), BC: 0.7 (−45.4), NO2: −14.1 (−47.0), SO2: −0.2 (−19.4) |
| (Tobias et al., 2020) | Spain (Barcelona) | Before lockdown: February 16th to March 13th, 2020 vs During lockdown: March 14th to 30th March 2020 | Remote sensing data, Copernicus Sentinel-5 | NO2 | PM10: −2.7 (−27.8), BC: 0.7 (−45.4), NO2: −14.1 (−47.0), SO2: −0.2 (−19.4) |
| (Nadzir et al., 2020) | Malaysia (Klang Valley) | Before lockdown: (28th November 2019 to 17th April 2020), During lockdown: 18th March–31st March 2020 (1st phase), 1st April–14th April 2020 (2nd phase), | SAQMSs (5 stations: industrial, residential, and traffic), air sensor network AiRBOXSense | CO, PM2.5, PM10 | PM10: (−14.2 to −51.8), CO: (−40.5 to −47.5), PM2.5: (41.2 to −58.9) |

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Table 2 (continued)

| Study ID | Country/Cities | Methodology | Sources of air quality data | Air pollutants | The changes of ambient air pollutants |
|----------|----------------|-------------|----------------------------|----------------|--------------------------------------|
| (Le et al., 2020) China (Wuhan) | and 15th April–28th April 2020 (3rd phase) 04/30/2018–04/29/2019 vs 04/30/2019–02/24/2020 | Satellite data (Ozone monitoring instrument (OMI) on the launched Aura satellite) | NO₂ | Concentration (percent changes) | Concentration (percent changes) |
| (Kanniah et al., 2020) Malaysia (Kuala Lumpur) Singapore (Singapore) Thailand (Bangkok) Vietnam (Hanoi) Vietnam (Ho Chi Minh city) Indonesia (Jakarta) Philippine (Manila) Cambodia (Phnom Penh) Laos (Vientiane) Myanmar (Yangon) Malaysia, 12 cites | First-quarter of 2020 (January, February, and March) vs the same period of the past year | SAQMSs (7 stations: industrial, traffic, and residential) | PM₂.₅ | 2018: (−28.0), 2019: (−29.0) and 2020: (−39.0) | |
| (Otmani et al., 2020) Morocco (Salé city) | Before lockdown: 21 February to 18 March and During lockdown: March 19 to April 14, 2020 (27 days), compared to the same period of 2018 and 2019 | Sampling (6 locations: industrial, residential and traffic) | BTEX | Benzene (+199.0), Toluene (+110.0) Ethylbenzene (−72.0), o-Xylene (−61.0) | |
| (Kerimray et al., 2020) | Before the lockdown (March 2 - March 18, 2020) vs During lockdown (March 19 – April 14, 2020) | SAQMSs (one traffic station) | NO₂, SO₂, CO, O₃ | O₃: +4.0 (+15.0), SO₂: +3.0 (+7.0) NO₂: −13.0 (−35.0), CO: −331.0 (−49.0) | |
| (Otmani et al., 2020) Morocco (Salé city) | Before the lockdown: (March 11th to 20th) and During the lockdown (March 21st to April 2nd) 2020 | Sampling in an urban residential area (High volume for PM₁₀ and electrochemical sensors for NO₂ and SO₂) | PM₁₀, NO₂, and SO₂ (μg/m³) | PM₁₀: −86.3 (−75.0), NO₂: −5.4 (−96.0), SO₂: −3.3 (−49.0) | |
| (Kanniah et al., 2020) Malaysia (Kuala Lumpur) Singapore (Singapore) Thailand (Bangkok) Vietnam (Hanoi) Vietnam (Ho Chi Minh city) Indonesia (Jakarta) Philippine (Manila) Cambodia (Phnom Penh) Laos (Vientiane) Myanmar (Yangon) Malaysia, 12 cites | Averaged over a window of 15-days on 1 March, 31 March, and 17 April 2020 vs compared to 5-years average values, Phase I: 1th March, Phase II: 31th March, and Phase III: 17th April | Satellite data (Aura-OMI) | NO₂ | Phase I: (+25.0), Phase II: NR, and Phase III: (+3.0) and Phase III: (+1.0) | Phase I: (−9.0) |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−34.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
| | | | | | Phase I: (−5.0), Phase II: (0.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−31.0) and Phase III: (−34.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
| | | | | | Phase I: (−5.0), Phase II: (0.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−34.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
| | | | | | Phase I: (−5.0), Phase II: (0.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−34.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
| | | | | | Phase I: (−5.0), Phase II: (0.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−34.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
| | | | | | Phase I: (−5.0), Phase II: (0.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−34.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
| | | | | | Phase I: (−5.0), Phase II: (0.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−10.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−34.0) and Phase III: (−9.0) | |
| | | | | | Phase I: (−4.0) and Phase III: (−6.0) | |
Vietnam, Indonesia, Malaysia, Philippine, Cambodia, Laos, UAE, Myanmar), African countries (Morocco), Europe (Spain, Italy, and non-methane hydrocarbons (NMHC)) in the studies have been investigated in two ways: 1) more studies compared the average concentrations of ambient air pollutants during the lockdown measures in each country or city with those before lockdown bans in the same year, and 2) the rest of studies compared the average concentrations of ambient air pollutants during the lockdown measures with those during the same period of the previous year/years. In addition to ambient particulate matter and gaseous air pollutants, two studies reported the changes in Aerosol Optical Depth (AOD). Furthermore, a few studies investigated the air quality index (AQI). The reviewed studies have investigated the impact of lockdown measures on the anthropogenic and natural sources and their emissions using the data collected from stationary ground-based air quality monitoring stations (e.g., traffic, industrial, residential, and rural/background stations), satellite methods, and sampled air pollutants by samplers.

As shown in Table 2, approximately all ambient air pollutants, except ambient O₃, declined remarkably on a global scale. Therefore, the COVID-19 pandemic, as a new global challenge, caused a significant improvement in the ambient air quality status around the world. Graphs with the flags of different countries (Figs. 2 to 7) were used to illustrate the changes of criteria air pollutants (PM₂.₅, PM₁₀, NO₂, NOₓ, NO, O₃, SO₂, CO, black carbon, BTEX (benzene, toluene, ethylbenzene, o-Xylene), NH₃, and non-methane hydrocarbons (NMHC)) in the studies have been investigated in two ways: 1) more studies compared the average concentrations of ambient air pollutants during the lockdown measures in each country or city with those before lockdown bans in the same year, and 2) the rest of studies compared the average concentrations of ambient air pollutants during the lockdown measures with those during the same period of the previous year/years. In addition to ambient particulate matter and gaseous air pollutants, two studies reported the changes in Aerosol Optical Depth (AOD). Furthermore, a few studies investigated the air quality index (AQI). The reviewed studies have investigated the impact of lockdown measures on the anthropogenic and natural sources and their emissions using the data collected from stationary ground-based air quality monitoring stations (e.g., traffic, industrial, residential, and rural/background stations), satellite methods, and sampled air pollutants by samplers.

3.3. The implemented lockdown restrictions to prevent the spread of COVID-19 around the world

To better control the COVID-19 pandemic, the international public health bodies (e.g., World Health Organization and U.S. Centers for Disease Control and Prevention) have recommended that people stay at home (Lancet, 2020). As a result, the partial to complete lockdown restrictions were adopted and immediately implemented by countries worldwide. Table 1 gives detailed information concerning the countries and the type of lockdown actions, implementing to minimize the virus spread. The implemented lockdown measures consisted of closing down public transportation, religious public places, school/universities, businesses, shopping centers (except for essential services), industrial activates (except for crucial industries), the public entertainment places (Parks, Beaches, Restaurants, etc.) and the movements (traveling between states and abroad). We also reported the results of the reviewed studies based on the implemented stages in Figs. 2 to 7. Table 2 gives detailed information on lockdown measures implemented in various phases and step by step in included countries. It should be noted that the lockdown measures had been implemented in multiple phases in the countries and cities under study (Chauhan and Singh, 2020; Collivignarelli et al., 2020; Kanniah et al., 2020). Some countries and cities implemented the complete lockdown, whereas others have applied partial measures. As a result, the reduction of ambient air pollutants can be varied there.

3.4. The effects of COVID-19 pandemic on the ambient air quality around the world

Table 2 summarizes the results of included studies investigating the indirect effects of COVID-19 pandemic lockdown measures on the ambient air quality status worldwide; a totally of 19 countries, mostly from Asia (China, India, Singapore, Kazakhstan, Thailand, Vietnam, Indonesia, Malaysia, Philippine, Cambodia, Laos, UAE, Myanmar), African countries (Morocco), Europe (Spain, Italy, France), Southern America (Brazil) and the USA. Besides, the applied methodology, the form of air quality data, the type of ambient air pollutants, and the relevant findings are outlined in Table 2. The changes of ambient air pollutants (PM₂.₅, PM₁₀, NO₂, NOₓ, NO, O₃, SO₂, CO, black carbon, BTEX (benzene, toluene, ethylbenzene, o-Xylene), NH₃, and non-methane hydrocarbons (NMHC)) in the studies have been investigated in two ways: 1) more studies compared the average concentrations of ambient air pollutants during the lockdown measures in each country or city with those before lockdown bans in the same year, and 2) the rest of studies compared the average concentrations of ambient air pollutants during the lockdown measures with those during the same period of the previous year/years. In addition to ambient particulate matter and gaseous air pollutants, two studies reported the changes in Aerosol Optical Depth (AOD). Furthermore, a few studies investigated the air quality index (AQI). The reviewed studies have investigated the impact of lockdown measures on the anthropogenic and natural sources and their emissions using the data collected from stationary ground-based air quality monitoring stations (e.g., traffic, industrial, residential, and rural/background stations), satellite methods, and sampled air pollutants by samplers.

As shown in Table 2, approximately all ambient air pollutants, except ambient O₃, declined remarkably on a global scale. Therefore, the COVID-19 pandemic, as a new global challenge, caused a significant improvement in the ambient air quality status around the world. Graphs with the flags of different countries (Figs. 2 to 7) were used to illustrate the changes of criteria air pollutants (PM₂.₅, PM₁₀, NO₂, O₃, SO₂, and CO) in the countries and cities under study. As shown in Figs. 2 to 7, the lockdown measures related to COVID-19 pandemic decreased the levels of ambient PM₂.₅ (Fig. 2), NO₂ (Fig. 3), PM₁₀ (Fig. 4), SO₂ (Fig. 5) and CO (Fig. 6) air pollutants in the range of 2.9%–76.5%, 18.0%–96.0%, 6.0%–75.0%, 6.8%–49.0% and 6.2%–64.8%, respectively. Compared to other air pollutants, O₃ increased during the lockdown measures in the range of 2.4%–252.3% (Fig. 7). Regarding PM₂.₅ as the most notable marker of ambient air pollution, the highest reduction was found for Malaysia (76.5% and 58.9%), followed by Zaragoza (Spain) with 58.0%, Delhi (India) with 53.1% during the first phase of lockdown measures, Beijing and Shanghai (China) with 50.0% at the second and first phase of lockdown measures, and Milan with 47.0% (Italy). For PM₂.₅, the lowest reduction was recorded for Nice (France) with 2.9%, São Paulo with 3.6% (Brazil) during the second phase of lockdown measures, Los Angeles with 4.0% at the first phase of lockdown measures and Dubai (UAE) with 6.0% and 11.0% over the second and first phases of lockdown measures. Among the included studies, P. Sicard et al. (2020) stated that ambient PM₂.₅ increased equal to 10.6% compared to the same period averaged over the three years/periods. In addition to ambient particulate matter and gaseous air pollutants, two studies reported the changes in Aerosol Optical Depth (AOD). Furthermore, a few studies investigated the air quality index (AQI). The reviewed studies have investigated the impact of lockdown measures on the anthropogenic and natural sources and their emissions using the data collected from stationary ground-based air quality monitoring stations (e.g., traffic, industrial, residential, and rural/background stations), satellite methods, and sampled air pollutants by samplers.
previous years (2017–2019). In contrast, other studies reported decreases of 24.0% and 46.0% during the second and third phases of Rome’s lockdown measures (Italy). For NO$_2$, all countries and cities experienced a significant reduction compared to before lockdown or the same period of last year/years. The highest decline was found for Salé city (Morocco) with 96.0%, followed by Mumbai (India) with 75.0% during the first phase of lockdown measures, India with 70.0%, Valencia (Spain) with 69.0% and São Paulo (Brazil) with 68.0%, respectively. Furthermore, the lowest reduction of NO$_2$ was recorded for 22 cities of India with an average of 18.0%, Yangtze River Delta region in China with 18.5%, São Paulo (Brazil) with 21.4% over the second phase of lockdown measures, and 337 major cities of China with 25.0%. Like ambient NO$_2$, CO declined in all countries and cities compared to before lockdowns or the same period of last year/years. São Paulo (Brazil), Milan (Italy), and Almaty (Kazakhstan) with 64.8%, 57.6%, and 49.0% had the highest reduction of CO levels compared to other study under study. In comparison, the lowest decrease of CO concentrations was recorded for 337 major cities in China (6.2%), the Yangtze River Delta region in China (7.8%) during the first phase of lockdown measures and 22 cities of India (10.0%). The highest reduction of ambient PM$_{10}$ levels was recorded for Salé City (Morocco) with 75.0%, Delhi (India) in the range of 51.8%–56.5% and Klang Valley (Malaysia) with 51.8% during the lockdown restrictions in comparison to before lockdowns or the same period of last year/years, whereas the lowest was found for Nice (France) and Turin (Italy) with 5.9% and 8.9%, respectively. Among all countries and cities under investigation, Salé city (Morocco) with 49.0%, Wuhan, Jinmen, Enshi (China) with 45.0%, and Hubei Province (China) with 33.4% experienced the highest reduction of ambient SO$_2$. For SO$_2$, the lowest reduction was found in Milan (Italy) with 6.8% and 19.9% during the first and third phases of lockdown measures, and Delhi (India) with 18.0%. As described above, contrary to other criteria air pollutants, we observed an increase in the levels of ambient O$_3$ in all countries and cities under study. The highest increase was recorded for Milan (Italy) with 252.3% and 169.9% during the first and third phase of lockdown measures, and Kolkata (India) with 87.0% at the second phase of lockdown measures. As discussed above, there was a variation in the reduction of ambient air pollutants in the countries and cities as the degree of lockdown measures had varied there.

4. Discussion

4.1. Reasons for improving ambient air quality reported by the studies during the lockdown restrictions and recommendations for the future researches

Table S3 shows detailed information concerning sources of ambient air pollution in the reviewed countries and cities and their reasons for improving ambient air quality. The countries and cities under study adopted and implemented stringent restrictions on various sectors to better control the COVID-19 pandemic (Table 1 and Table S3). The major ambient air pollutants (PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and CO) in the countries and cities under investigation arise from a broad range of anthropogenic and natural sources such as vehicular emissions (as the most notable source of ambient air pollution globally), industrial units, power generation, residential heating, agricultural burning, wildfires, resuspended dust, and dust storm events. The ambient air quality data from stationary ground-based monitoring stations (e.g., traffic, industrial, residential, rural, and background stations) and satellite methods were used to show the effect of lockdown measures on aforementioned emission sources and therefore, the emissions of ambient air pollutants. Approximately all studies have reported that road and non-road transportation and commercial activities as the main contributors to ambient air pollution in urban areas declined drastically; thereby the level of all ambient air pollutants experienced a significant reduction in the countries and cities over the world. However, the emissions from residential heating and essential industry remained steady or slightly declined. All studies believe that the restrictions on various sectors are the main reasons to reduce all ambient air pollutants’ levels, except for O$_3$. As a secondary air pollutant, O$_3$ is formed by photochemical reactions among its precursors, in particular, nitrogen oxides (NOx) and volatile organic compounds (VOCs). The increase in O$_3$ concentration can be a consequence of the following possible causes. Firstly, the decline of ambient NOx in a VOC-limited urban environment might cause an increase in the formation of O$_3$ (Sicilianio et al., 2020; Tobias et al., 2020). Secondly, the decrease of titration of O$_3$ by NOx due to the observed significant reduction in local NOx emissions’ sources (Mahato et al., 2020; Nakada and Urban, 2020; Tobias et al., 2020; Youssefian et al., 2020). Thirdly, it may be related to the observed declines in PM$_{2.5}$ leads to a rise in solar activity levels and an increase of O$_3$ concentration. Finally, the lower ambient PM$_{2.5}$ during the lockdown restrictions would be a less effective sink for the radicals of hydroperoxy (HO$_2$) increasing the proxy radical-mediated O$_3$ formation (Jafari et al., 2019; Kerimray et al., 2020; Wang et al., 2020).

Source apportionment approach is capable of better identify local sources (on-road vehicles, industry, domestic, and others) of air pollution affected by the COVID-19 lockdowns and estimating their contributions during the COVID-19 lockdowns (Dai et al., 2020; Lv et al., 2020; Wang et al., 2021). Finally, we highlight future research needs for utilizing the positive matrix factorization (PMF) to better show ambient particulate matter sources and quantify the contributions of source affected by the COVID-19 lockdowns. According to the levels of economic development of countries, health-based priorities, the abatement policies of environmental risk factors, ambient air pollutant levels, the sources of ambient air pollution and their contributions in the cities around the world are differ (Hopke et al., 2020; Karagulian et al., 2015; Karagulian et al., 2017; Mukherjee and Agrawal, 2017), thereby the effect of implemented lockdown measures on them can be varied (Dai et al., 2020). A more recent recently study authored by (Dai et al., 2020) has provided insights into the significant changes in source contributions to PM$_{2.5}$ and its chemical components during the COVID-19 pandemic in the Jinan district of Tianjin, China using dispersion normalized positive matrix factorization. Their results revealed significant changes in source contributions during the COVID-19 pandemic (Dai et al., 2020). Moreover, the source apportionment study of (Tian et al., 2021) and (Lin et al., 2021) highlighted that lockdown measures attributed to the COVID-19 pandemic affected the concentrations and relative contributions of primary emissions, secondary aerosol formation and carbonaceous aerosols compared to before lockdown.

The most considerable fraction of the studies used ground-based measurements in their analysis that these data have immediately
reflected the effect of human-being activities on ambient air quality. Around one-third of included studies used satellite observations, that 23% of the studies used Sentinel-5P Tropospheric Monitoring Instrument and the rest of them used AURA-OM, NASA, and Himawari-8. Only two studies have applied the sampling. About 65% of studies have conducted in Asia with highly polluted countries and the rest of ones related to the USA and Europe, and three studies considered multiple countries. Around 60% of studies compared the air quality during the lockdown with the same period in last years; however, the others considered the air quality during the lockdown (commonly in spring) versus before lockdown (winter) in a year. As shown in Table 2, the studies have used various platforms to measure ambient air pollutant concentrations and different methods to determine lockdown effects on ambient air pollutants. As a result, these differences could lead to considerable uncertainty for comparing their results. Additionally, given the speed with which manuscripts regarding the COVID-19 lockdown effects were prepared and published, it is possible that many are based on data with no final quality control. Consequently, we emphasize the need to control and validate air quality data prior to accounting the effect of COVID-19 lockdown on ambient air quality in the future researches.

4.2. Mobility index (MI) and meteorological parameters (MPs) during the lockdown restrictions

In addition to reasons reported by the studies mentioned above (section 4.1 and Table S3), we examined the MPs (excluded from the reviewed articles) and the MI from both Apple (https://covid19.apple.com/mobility) and Google (https://www.google.com/covid19/mobility/) during the lockdown restrictions that better explain the results of reviewed studies. Both MI datasets reveal a relative trend of how people’s movements changed within countries and cities during the lockdown restrictions related to the COVID-19 pandemic (Archer et al., 2020; Le et al., 2020). Google’s and Apple’s MI data can be considered as a proxy of human mobility affecting the ambient air pollutants’ emissions (Archer et al., 2020; Bao and Zhang, 2020; Chen et al., 2020; Le et al., 2020; Muhammad et al., 2020). Google’s MI dataset has been built from the data collected from people who allowed Google to access their location information. This MI dataset is classified into retail and recreation, grocery and pharmacy, parks and outings, transit stations, workplaces, and residential categories (details in Table 3). The data released from Jan 13, 2020, reflects how the lockdown restrictions imposed by the countries and cities impacted each category compared to the baseline (the median value, for the corresponding day of the week, during the five-week from Jan 3 to Feb 6, 2020). Furthermore, Apple’s MI dataset is based on the direction requested by people in Apple Maps and classified into the following categories: driving by personal vehicles, public transit (such as subway, bus, train, and taxi stations), and walking (details in Fig. 8, Fig. S2 and Table S1). The levels of all categories of Google’s MI, except for people’s residential movements, declined during the lockdown bans in the studied countries and cities (Table 3). The decrease of the latter sector confirms that intra city migration index as the main factor affecting the emission sources declined during the lockdown bans (Archer et al., 2020; Bao and Zhang, 2020; Le et al., 2020). Given Apple’s MI dataset (Fig. 8 and Fig. S2), an interesting pattern was discovered for MI related to driving, transit and walking before and after lockdown restrictions. The data shows that MI has reduced in the range of approximately 30–88% for driving by personal vehicles, 45–94% for public transit, and 37–94% for walking. The highest reductions for the driving sector were observed in Spain, Italy, India, and France (Fig. 8), whereas the lowest declines were recorded in Singapore, Vietnam, the USA, Brazil, and their cities. Concerning public transit, Italy, Spain, and France experienced the highest reductions during the lockdown restrictions compared to other countries. Of 26 reviewed articles, only one study estimated the MI using a quantitatively developed model and reported the effect of lockdown measures on MI (Bao and Zhang, 2020). As expected, this study confirmed that the reduction in human mobility was significantly associated with the implemented bans and led to a

| Location      | Retail and recreation | Grocery and pharmacy | Parks and outing | Public transit | Workplaces | Residential |
|---------------|----------------------|----------------------|-----------------|---------------|------------|-------------|
| Brazil        | −51%                 | −4%                  | −53%            | −41%          | −3%        | +11%        |
| Cambodia      | −15%                 | −10%                 | −6%             | −38%          | −9%        | +4%         |
| France        | −6%                  | +9%                  | +82%            | −8%           | +9%        | −2%         |
| India         | −68%                 | −23%                 | −57%            | −8%           | −20%       | +14%        |
| Indonesia     | −20%                 | −2%                  | −35%            | −2%           | +8%        |
| Italy         | −18%                 | −17%                 | +56%            | −12%          | +7%        | −6%         |
| Kazakhstan    | −43%                 | −25%                 | +1%             | −11%          | −16%       | +3%         |
| Laos          | +3%                  | +9%                  | −14%            | −19%          | +2%        | −1%         |
| Malaysia      | −23%                 | −3%                  | 0%              | −19%          | −15%       | +5%         |
| Morocco       | −22%                 | −11%                 | −3%             | −31%          | −9%        | +7%         |
| Myanmar (Burma)| −11%                | −1%                  | −13%            | −14%          | −2%        | +8%         |
| Philippines   | −57%                 | −30%                 | −38%            | −62%          | −20%       | +18%        |
| Singapore     | −29%                 | −9%                  | −25%            | −38%          | −13%       | +15%        |
| Spain         | −24%                 | +2%                  | +28%            | −30%          | +5%        | −3%         |
| Thailand      | +1%                  | +14%                 | +13%            | −26%          | −13%       | +2%         |
| UAE           | −24%                 | −3%                  | −45%            | −47%          | −24%       | +14%        |
| USA           | −22%                 | −10%                 | +53%            | −23%          | +19%       | +3%         |
| Vietnam       | −10%                 | +5%                  | −14%            | −4%           | −6%        | +6%         |

1 Places like restaurants, cafes, shopping centers, theme parks, museums, libraries, and movie theaters.
2 Places like grocery markets, food warehouses, farmers’ markets, specialty food shops, drug stores, and pharmacies.
3 Places like national parks, public beaches, marinas, dog parks, plazas, and public gardens.
4 Public transit hubs such as subway, bus, and train stations.
Fig. 8. Extracted Mobility Index from the COVID-19 Community Mobility Report for the Spain (a), Italy (b), India (c) and France (d) before and during lockdown.
4.3. The threat of ambient air pollution to human health and lessons from COVID-19 pandemic to reduce it

Determination of COVID-19 lockdown effects on ambient air pollutant concentrations in the future researches. Lelieveld et al., 2015). Among ambient air pollutants, PM\(_{2.5}\) were identified as the fifth-ranked cause of global disease burden in 2015 (Al-Kindi et al., 2020; Burns et al., 2020; Janjani et al., 2020; Paunescu et al., 2019; Rajagopal et al., 2018). Global premature deaths attributed to ambient PM\(_{2.5}\) rose considerably from 3.5 million in 1990 to 4.2 million in 2015 (Cohen et al., 2017). The loss of life expectancy due to long-term exposure to air pollution exceeds that of infectious diseases worldwide (Pozzer et al., 2020). It is also interesting to note that several studies show the association between exposure to air pollution and increased risk of COVID-19 lethality (Conticini et al., 2020; Contini and Costabile, 2020; Copat et al., 2020; Petroni et al., 2020; Yao et al., 2020; Yongjian et al., 2020). Air pollution affects the body’s immunity, particularly the respiratory system, making people more vulnerable to COVID-19 infection (Conticini et al., 2020; Contini and Costabile, 2020; Copat et al., 2020; Petroni et al., 2020). More recently studies revealed that exposure to ambient PM\(_{2.5}\) air pollution is an essential cofactor increasing the risk of mortality from COVID-19 infection (Giani et al., 2020; Pozzer et al., 2020). It has been estimated that exposure to ambient PM\(_{2.5}\) air pollution from all anthropogenic and fossil fuel-related emissions contributed approximately 15% (95% confidence interval 7–33%) and 8% (4–25%) to COVID-19 infection mortality globally (Pozzer et al., 2020). As a driving force, COVID-19 pandemic revealed that air pollution is a controllable and modifiable risk factor because this pandemic as a global challenge has compelled the countries around the world to implement a part of societal and governmental interventions (as mentioned in Table 1) which had been effective in reducing air pollution emissions (Abdullah et al., 2020; Bao and Zhang, 2020; Burns et al., 2020; Chauhan and Singh, 2020). In reality, COVID-19 pandemic can be considered as a window of opportunity for accelerating in-depth and comprehensive implementation of all well-documented multisector policies and approaches (e.g., shifting to clean fuels, transportation reform, reduce traffic emissions, urban landscape reform, emission trading programs, redirection of science and funding, empowering civil society, Governmental and NGO-led publicity) to mitigate exposure to air pollution and its health effects at the local, regional, and global levels in the future (Bard et al., 2019; Burns et al., 2020; Faridi et al., 2020b; Giles et al., 2010; Hadley et al., 2018; Pozzer et al., 2020; Rajagopal et al., 2018; Sanchez et al., 2020; van Dorn, 2017). In addition to previously air pollution mitigation policies documented, all nations learned that can adopt and continue to limit non-essential individual- and population-level travel by teleworking (Mannucci, 2020). Also, all developed and developing countries should avoid quickly forgetting the lessons learnt during the COVID-19 pandemic, because they experienced significant achievements in reducing air pollution (Mannucci, 2020). We all believe that continuous air pollution mitigation strategies at the local, regional, and global levels might help in decreasing the fatality rate not only over the ongoing COVID-19 pandemic but also in probable future pandemics related to respiratory diseases (Contini and Costabile, 2020; Copat et al., 2020; Giani et al., 2020). Finally, the COVID-19 pandemic will end with the population’s vaccination or with herd immunity (Pozzer et al., 2020). However, there are no vaccines against air pollution and its health effects (Pozzer et al., 2020). The only remedy for declining air pollution and its health consequences is the strict implementation of societal and governmental interventions (Pozzer et al., 2020).
5. Conclusion

Responding to the coronavirus disease 2019 (COVID-19) outbreak, countries mandatorily or inevitably implemented the lockdown measures, as a result, ambient air quality status markedly improved over the world. In the present study, we systematically reviewed the twenty-six included studies investigating the indirect effects of the COVID-19 pandemic on the ambient air quality status worldwide. The implemented lockdown measures related to the COVID-19 pandemic decreased ambient PM$_{2.5}$, NO$_2$, PM$_{10}$, SO$_2$ and CO air pollutants in the range of 2.9%–76.5%, 18.0%–96.0%, 6.0%–75.0%, 6.8%–49.0% and 6.2%–64.8% in the countries and cities throughout the world. O$_3$ rose during the lockdown measures in the range of 2.4%–252.3%, in stark contrast to other air pollutants. We hope that the COVID-19 pandemic can be considered as a window of opportunity for accelerating the in-depth and comprehensive implementation of all well-documented multisector policies and approaches to mitigate exposure to air pollution and its health effects at the local, regional, and global levels in the future.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2021.100888.

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