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Invited review article

Air quality changes in cities during the COVID-19 lockdown: A critical review

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ABSTRACT

In response to the rapid spread of coronavirus disease-2019 (COVID-19) within and across countries and the need to protect public health, governments worldwide introduced unprecedented measures such as restricted road and air travel and reduced human mobility in 2020. The curtailment of personal travel and economic activity provided a unique opportunity for researchers to assess the interplay between anthropogenic emissions of primary air pollutants, their physical transport, chemical transformation, ultimate fate and potential health impacts. In general, reductions in the atmospheric levels of outdoor air pollutants such as particulate matter (PM), nitrogen dioxide (NO₂), carbon monoxide (CO), sulfur dioxide (SO₂), and volatile organic compounds (VOCs) were observed in many countries during the lockdowns. However, the levels of ozone (O₃), a secondary air pollutant linked to asthma and respiratory ailments, and secondary PM were frequently reported to remain unchanged or even increase. An increase in O₃ can enhance the formation of secondary PM_{2.5}, especially secondary organic aerosols, through the atmospheric oxidation of VOCs. Given that the gaseous precursors of O₃ (VOCs and NO_x) are also involved in the formation of secondary PM_{2.5}, an integrated control strategy should focus on reducing the emission of the common precursors for the co-mitigation of PM_{2.5} and O₃ with an emphasis on their complex photochemical interactions. Compared to outdoor air quality, comprehensive investigations of indoor air quality (IAQ) are relatively sparse. People spend more than 80% of their time indoors with exposure to air pollutants of both outdoor and indoor origins. Consequently, an integrated assessment of exposure to air pollutants in both outdoor and indoor microenvironments is needed for effective urban air quality management and for mitigation of health risk. To provide further insights into air quality, we do a critical review of scientific articles, published from January 2020 to December 2020 across the globe. Finally, we discuss policy implications of our review in the context of global air quality improvement.

1. Introduction

In December 2019, the first case of COVID-19 caused by SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) was reported in Wuhan City, China (Huang et al., 2020). Within a short period of time COVID-19 spread to nearly all other parts of the world and was declared a pandemic by the World Health Organization (WHO) on 11 March 2020. Globally, there have been 203,295,170 confirmed cases of COVID-19 infections, including 4,303,515 deaths as of 10 August 2021 (<https://covid19.who.int/>). To limit the transmission of COVID-19, many countries enforced quarantine and imposed lockdown measures, resulting in a reduction in industrial activities, transportation and human movement. Only essential industries and services were allowed

to operate, leading to severe economic repercussions (Nicola et al., 2020). In contrast to the negative impacts of the pandemic on the economy and society, outdoor air quality (OAQ) was found to have improvement in many parts of the world due to reductions in the emissions of primary air pollutants from major sources such as vehicular traffic and industries. This observation indicates that air pollution can be a direct consequence of economic growth and human activities (e.g., Bao and Zhang, 2020; He et al., 2020a; Mahato et al., 2020; Piccoli et al., 2020). The unprecedented natural experiment conducted on a global scale in a controlled manner can be used to improve our understanding of changes in air quality and their causes. This scientific understanding will in turn form a basis for formulating effective environmental policies to improve global air quality by curbing emissions of air pollutants from

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appropriate anthropogenic sources.

Reductions in the atmospheric levels of criteria air pollutants, i.e., particulate matter (PM; PM₁₀ and PM_{2.5} (PM with diameter $\leq 10 \mu\text{m}$ and $\leq 2.5 \mu\text{m}$, respectively)), nitrogen dioxide (NO₂), carbon monoxide (CO), sulfur dioxide (SO₂), and ozone (O₃) have been reported in many cities during the lockdown, compared to pre-lockdown periods and/or previous years. The change in air quality was studied based on measurements of these criteria air pollutants at routine fixed monitoring stations and satellite-based observations (Bao and Zhang, 2020; Collivignarelli et al., 2021; Dantas et al., 2020; Le et al., 2020; Rodríguez-Urrego and Rodríguez-Urrego, 2020; Sulaymon et al., 2021; Venter et al., 2020). Several cities, however, did not experience an obvious improvement in OAQ, with some of them even observing a worsening of the air quality. These inconsistencies in observational data might be due to variations in meteorological factors, or the role of atmospheric chemistry while having clearing skies. For example, the surface levels of O₃, a secondary air pollutant, have frequently been reported to be stable or even increasing (e.g., Bekbulat et al., 2021; Nie et al., 2021; Sicard et al., 2020; Tobías et al., 2020; Zoran et al., 2020). Also, the level of secondary PM, as reported in studies investigating the chemical composition of PM, has been found to be similar or higher during the lockdown period compared to other times in a year (Huang et al., 2021b; Sun et al., 2020; Wang et al., 2021). These unexpected observations merit further

investigations in the context of furthering our scientific understanding of the formation of secondary air pollutants, their transport and evolution under different meteorological conditions, their impacts on human health as well as the effectiveness of current air pollution control strategies.

The stay-at-home policies mandated by the governments around the world meant that local populations spend almost all their time in indoor environments. As a consequence, emissions of PM and volatile organic compounds (VOCs) from daily activities such as cooking, cleaning and indoor smoking can potentially expose indoor occupants to harmful levels of air pollutants (Morawska et al., 2020; Saha and Chouhan, 2020; Stabile et al., 2020). Indoor air quality (IAQ), therefore, becomes an important consideration for human health and well-being (Morawska et al., 2013; Morawska et al., 2017; Wolkoff, 2018). In a lockdown/quarantine/telecommuting situation as experienced in 2020–2021 and potentially in the future, IAQ assessment merits a serious consideration with respect to human health. However, following the outbreak of COVID-19 and subsequent lockdowns, only few studies investigated IAQ systematically (e.g., Domínguez-Amarillo et al., 2020; Guo et al., 2020; Saha and Chouhan, 2020; WHO, 2020a). There is a lack of comprehensive studies on IAQ in comparison to OAQ. Also, the role of bio-aerosols, aerosols of biological origin such as metabolites, toxins, or fragments of microorganisms (Humbal et al., 2018; Kim et al., 2018) in

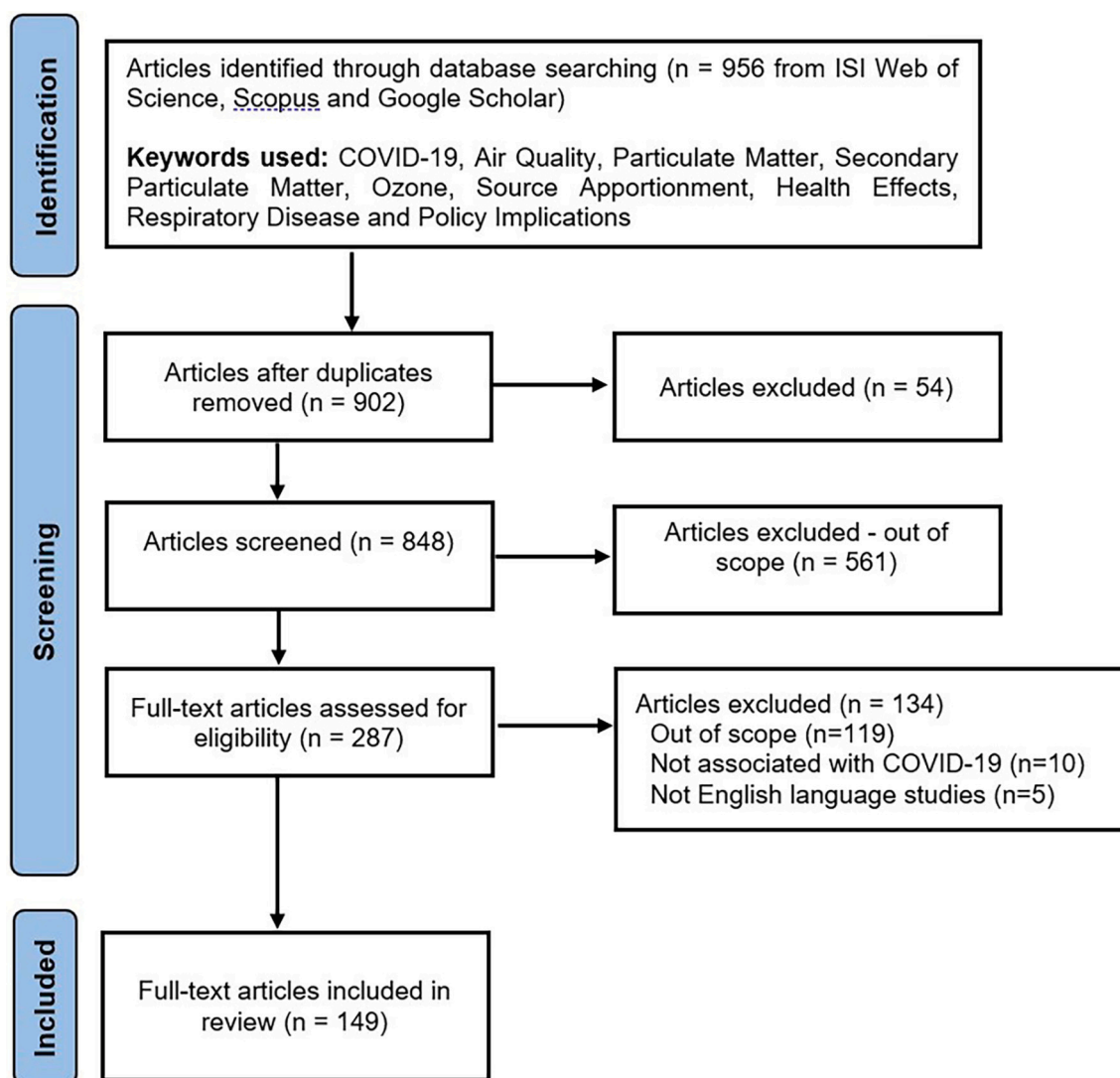


Fig. 1. PRISMA flow diagram of article selection process.

facilitating the airborne transmission of COVID-19 indoors has been insufficiently addressed. Furthermore, air pollutants such as PM have been implicated in contributing to the severity of COVID-19 health impacts (Conticini et al., 2020; Fattorini and Regoli, 2020; Frontera et al., 2020). This is similar to findings made during the 2003 SARS outbreak in China where a positive association was observed between both acute and chronic health outcomes and the air pollution index (indicator of the levels of PM₁₀, PM_{2.5}, CO, NO₂, SO₂ and O₃) (Cui et al., 2003). Exposure to high levels of air pollutants would directly affect the lung capacity to clear pathogens. Conversely, some studies suggest that after the outbreak of COVID-19, mortality reductions were achieved in countries/cities with lower levels of air pollution compared to those that are considered to be polluted (e.g., Chen et al., 2020b; Kumar et al., 2020; Son et al., 2020).

For the current review, we have considered 149 scientific articles that were published in the global domain from January 2020 up to December 2020 after the outbreak of COVID-19 in Wuhan, China (Asia), see Fig. S1. We selected these articles based on the criteria shown in Fig. 1 with more details given in the supplementary information. The review paper is structured in the following manner. Section 2 deals with the changes in OAQ in terms of sources, concentrations, chemical characteristics of air pollutants with emphasis on PM and O₃ and the impact of OAQ in COVID-19 outbreaks. Section 3 provides an overview of studies that investigated IAQ and their practical significance in terms of its impact on COVID-19 transmission. Section 4 discusses the policy implications as a result of the lessons that have been learned from the scientific studies covered in this review. Section 5 provides a summary of this review and points out future research directions. We believe that this critical review of air quality studies conducted on a global scale from multi-disciplinary viewpoints will enable the recommendation of targeted environmental policies for maintaining good OAQ as well as IAQ, leading to healthy living in cities.

2. Factors affecting OAQ and their impacts

2.1. Overview of OAQ studies

As shown in Table 1, a number of studies were conducted worldwide in 2020 to assess the effectiveness of lockdown measures imposed in various countries/cities on urban air quality. These studies predominantly reported differences in the concentrations of criteria air pollutants, i.e., PM₁₀/PM_{2.5}, ground-level O₃, SO₂, NO₂, and CO (see last column in Table 1). In general, decreases in the concentrations of the oxides of nitrogen (NO_x), CO and SO₂, were observed. Particularly, a large reduction in NO₂ (~70%) was reported in Spain (Sicard et al., 2020) and India (Gautam, 2020; Resmi et al., 2020). Such large reductions were also reported for SO₂ in Singapore (~52%, Li and Tartarini (2020)) and India (~62%, Resmi et al. (2020)) and for CO in Brazil (>30% up to 100%, Siciliano et al. (2020a)) and India (~70%, Resmi et al. (2020)). The decrease in the concentration of primary air pollutants has been mainly attributed to reduced emissions of air pollution from on-road vehicles and non-essential industries (Hudda et al., 2020; Rossi et al., 2020).

It should be noted that the improvement of urban air quality with respect to primary air pollutants did not show consistent temporal or spatial trends among cities within the same country and among different countries. This inconsistency arises from differences in the emission strengths of air pollutants from specific sources, the location of air pollution sources relative to fixed air quality monitoring stations, prevailing meteorology, chemical transformations of reactive air pollutants induced by atmospheric oxidants, and the effectiveness of their removal by atmospheric deposition processes. Air pollutants are emitted from a range of human-induced sources such as industries, on-road vehicles, ships, and aeroplanes, biomass burning and natural sources such as dust storms and oceans. During lockdowns, urban mobility was significantly restricted in most cities, leading to a reduction in transport-related air

pollution. However, the emission characteristics of traffic-related air pollutants not only depend on the volume of on-road vehicles, but also on the traffic composition (the relative counts of motorcycles, passenger cars, buses, utility vehicles, and heavy-duty trucks) (Tran et al., 2021a).

Some studies considered changes in traffic volume and composition while interpreting their observational data on air pollutants. For example, Siciliano et al. (2020a) explained that the reduction in the levels of CO, NO₂ and PM₁₀ in Brazil's two most populated cities (São Paulo and Rio de Janeiro) during the lockdown periods did not show a consistent pattern. This inconsistency was attributed to changes in the vehicular fleet characteristics in the two cities and the influence of other factors such as the transport of air masses from industrial and rural areas. In Singapore, PM₁₀, PM_{2.5}, NO₂, CO, and SO₂ decreased by 19, 23, 29, 54, 6, and 52%, respectively, while O₃ increased by 18% during the lockdown period in 2020 (April–May) compared to their concentrations observed in the same months from 2016 to 2019 (Li and Tartarini, 2020). The reduction in the levels of PM_{2.5} and NO₂ was mainly influenced by the reduced human mobility on road (Li and Tartarini, 2020). The changes in the concentrations of PM₁₀, CO, and SO₂ were attributed to the spatial distribution of other pollution sources such as industries, petroleum refineries and shipping-related activities in Singapore. In contrast to other air pollutants, the concentration of O₃ rather increased in Singapore which was also observed during the lockdown in several other cities (Chen et al., 2020c; Collivignarelli et al., 2020; Kerimray et al., 2020; Sulaymon et al., 2021). Reasons for the unexpected increase in the levels of O₃ are explained in a later section.

To get further insights, source apportionment (SA) of air pollutants using receptor models or chemical mass balance models is needed for developing effective air pollution control strategies (Hopke, 2016). However, only few studies, as shown in Section 2.2., investigated source characteristics of air pollutants with emphasis on PM using SA methods. The other reason for inconsistent results reported by different researchers in terms of improvements in urban air quality is the duration of lockdowns imposed in different countries. For example, China imposed a lockdown from 10 February to 14 March 2020, while India imposed 3 successive lockdowns from 25 March to 17 May 2020. The USA had its lockdown across the country from 19 March to April 30, 2020. Therefore, the volume of observational data obtained on criteria air pollutants differed significantly among countries worldwide. While comparing the concentrations of air pollutants measured during the lockdown to those obtained during pre- and post-lockdown periods, researchers used different protocols. Consequently, there was no consistency in the study outcomes. For example, some studies compared the levels of air pollutants measured during lockdowns to those obtained in the same year preceding and/or following the lockdown period (e.g., Abdullah et al., 2020; Cui et al., 2020; Siciliano et al., 2020a). Other studies considered either the same time period in previous years (2019/2018/2017) (e.g., Bekbulat et al., 2021; Chen et al., 2020b; Mahato et al., 2020; Singh and Chauhan, 2020) or a combination of both such time periods (e.g., Vadrevu et al., 2020). Meteorological conditions such as incoming solar radiation, ambient air temperature, relative humidity, wind speed and wind direction differ from one season to another within the same year. Consequently, the selection of pre- or post-lockdown period is critical in assessing the effectiveness of lockdown measures on urban air quality. Specifically, the transport, dispersion, distribution (both spatial and vertical) and concentration of air pollutants depend on seasonal variations of meteorological conditions.

In fact, several studies pointed out the importance of considering the role of meteorological conditions in explaining the changes in urban air quality during the lockdown (Ansari et al., 2019; He et al., 2017; Zhang et al., 2016). However, prevailing meteorological factors were seldom considered in the majority of lockdown-related air quality studies, which makes the comparison of study outcomes challenging to assess air quality improvements at regional and global scales. In addition to meteorology, the role of atmospheric chemistry in the conversion of reactive primary air pollutants such as SO₂, VOCs and NO_x to secondary

Table 1
Overview of studies related to outdoor air quality during the COVID-19 pandemic.

Study	Location	Type of study/method	Reference period	Air pollutants and changes observed in percent (%) during the lockdown compared to the reference period
Abdullah et al. (2020)	Malaysia (16 states)	Air quality monitoring station data	Before movement control order (14–17 March 2020)	PM_{2.5} : -42.6 to -76.5
Aman et al. (2020)	India	Remote sensing data	Same period of 2015-2019	Suspended Particulate Matter : -16.8 to -36.5
Barré et al. (2020)	Europe (100 locations)	Satellite data (TROPOMI), air quality monitoring station data, model simulations	Same period of 2019 (February, March, April)	NO₂ : +6.05% to -60.5%
Bekbulat et al. (2021)	USA (all states)	Air quality monitoring station data	Weeks in 2020 when the COVID-19 had little or no impact on activities	PM_{2.5} : +3.0, O₃ : -4.0, NO₂ : -30.0
Berman and Ebisu (2020)	USA	OpenAQ API	Pre-COVID-19 period (8 January 8th-12 March 2020)	PM_{2.5} : +3.51 to -11.26, NO₂ : -5.52 to -26.89
Chen et al. (2020a)	China (367 cities)	Satellite data (Sentinel-5)	Before quarantine period (5 Jan to 20 Jan 20)	NO₂ : -12.9 µg/m ³ , PM_{2.5} : -18.9 µg/m ³
Chen et al. (2020b)	China (Wuhan) China (366 urban areas)	Air quality monitoring station data	2019	NO₂ : -22.8 µg/m ³ , PM_{2.5} : -1.4 µg/m ³ PM_{2.5} : -14.0, PM₁₀ : -15.0, SO₂ : -12.0, NO₂ : -16.0, CO : +9.0
Collivignarelli et al. (2020)	Italy (Milan)	Air quality monitoring station data	7-20 Feb 2020	PM₁₀ : -(45.8 to 59.4), PM_{2.5} : -(47.1 to 47.4), BC : -71.0, Benzene : -65.0, CO : (-32.0 to -56.7), NO_x : (-58.6), SO₂ : Unchanged, O₃ : +66.0
Dantas et al. (2020)	Brazil (Rio de Janeiro)	Air quality monitoring station data	Same period of 2019	PM₁₀ : 28.7 to 19.4, NO₂ : -(24.1 to 32.9), CO : -(37.0 to 43.6), O₃ : +(22.5 to 63)
Evangelidou et al. (2020)	Europe (17 stations)	Air quality monitoring station data, satellite data, remote sensing data	Before lockdowns (2015-2019)	BC : -20.0 to -32.0
Gautam (2020)	China, India, Italy, Spain, France	Satellite data (Sentinel-5P)	Before lockdowns	NO₂ : -30.0 (China), -70.0 (India), -30.0 (Italy), -25.0 (Spain), -30.0 (France)
Giani et al. (2020)	Europe, China	Air quality monitoring station data,	Before lockdowns (2016-2019)	PM_{2.5} : -20.4 (Europe), -11.3 (China)
Hudda et al. (2020)	Somerville, Massachusetts, USA	Measurement campaign (CPC, Aethalometer)	Before lockdown (2012-2013, 2018-2019)	PNC : -45.0 to -69.0, BC : -22.0 to -56.0
Isaifan (2020)	China (Wuhan)	Satellite data (NASA)	Before quarantine (1-20 Jan 2020)	NO₂ : -30.0, CO : -25.0
Kanniah et al. (2020)	Indonesia (Jakarta), Malaysia (Kuala Lumpur), Singapore, Thailand (Bangkok), Vietnam (Ho Chi Minh, Hanoi), Philippines (Manila), Myanmar, Cambodia (Phnom Penh), Laos (Vientiane)	Satellite data (Aura-OMI)	Same periods in 2018 and 2019	NO₂ : -34.0 to +25.0
	Malaysia, 12 cities			O₃ : +3.0 to +7.0, PM₁₀ : -26.0 to -31.0, PM_{2.5} : -23.0 to -32.0, NO₂ : -63.0 to -64.0, CO : -25.0 to -32.0, SO₂ : -9.0 to -20.0
	Malaysia	Air quality monitoring stations		NO₂ : -40.0 to -60.0
		Satellite data (Himawari-8)		NO₂ : -40.0 to -60.0
Kerimray et al. (2020)	Kazakhstan (Almaty)	Air quality monitoring station data	Same days in 2018–2019	PM_{2.5} : -(6.0 to 34.0), CO : -49.0 NO₂ : -35.0, Benzene, toluene : 2 to 3 times higher
Krecl et al. (2020)	Brazil (Sao Paulo)	Air quality monitoring stations	Same seasons in 2015–2019 Business as usual (2-10 March 2020)	NO_x : -34.0 to -68.0
Kumar et al. (2020)	India (Chennai, Delhi, Hyderabad, Kolkata, Mumbai)	Air quality monitoring station data	Same period in 2015-2020	PM_{2.5} : -(19.0 to 43.0) (Chennai), -(41.0 to 53.0) (Delhi), -(26.0 to 54.0) (Hyderabad), -(24.0 to 36.0) (Kolkata), -(10.0 to 39.0) (Mumbai) NO₂ : -71.9 (Eastern) PM_{2.5} : -43.5 and O₃ : +25.1 (Wuhan) PM_{2.5} : +55.1 and O₃ : +25.1 (Beijing)
Le et al. (2020)	China	Satellite data (TROPOMI) and Air quality monitoring station	Same period in 2015-2019	PM_{2.5} : -53.0 to -31.0, NO₂ : -76.0 to -45.0, CO : -46.0 to -14.0, SO₂ : -20.0 to +5.0, O₃ : +31.0 to +88.0 O₃ : +0.78, PM₁₀ : -56.6 to -51.9, PM_{2.5} : -53.1 to -32.9, SO₂ : -18.0, NO₂ : -52.7, CO : -30.4, NH₃ : -12.3, AQI : -61.0
Liu et al. (2020a)	China (Yangtze River Delta)	Community Multiscale Air Quality (CMAQ) model	Before the lockdown (from 1-22 Jan 2020)	PM_{2.5} : -53.0 to -31.0, NO₂ : -76.0 to -45.0, CO : -46.0 to -14.0, SO₂ : -20.0 to +5.0, O₃ : +31.0 to +88.0 O₃ : +0.78, PM₁₀ : -56.6 to -51.9, PM_{2.5} : -53.1 to -32.9, SO₂ : -18.0, NO₂ : -52.7, CO : -30.4, NH₃ : -12.3, AQI : -61.0
Mahato et al. (2020)	India (Delhi)	Air quality monitoring stations	Pre-lockdown period	PM_{2.5} : -53.1 to -32.9, SO₂ : -18.0, NO₂ : -52.7, CO : -30.4, NH₃ : -12.3, AQI : -61.0

(continued on next page)

Table 1 (continued)

Study	Location	Type of study/method	Reference period	Air pollutants and changes observed in percent (%) during the lockdown compared to the reference period
Mohd Nadzir et al. (2020)	Malaysia (Klang Valley)	Air quality monitoring stations, Air sensor Network AirBOXSense	Normal days (Nov 2017 to April 2018)	PM ₁₀ : +14.2 to -51.8, CO: -40.5 to -47.5, PM _{2.5} : +41.2 to -58.9
Nakada and Urban (2020)	Brazil (Sao Paulo)	Air quality monitoring station data Satellite data (TROPOMI)	Same period in 2015-2019, Before and during partial lockdown (25 February to 23 March 2020; 24 March to 20 April 2020)	PM ₁₀ : -22.8 to +29.4, PM _{2.5} : -29.5 to -0.3, SO ₂ : -32.7 to +16.2, NO ₂ : -54.3 to +9.6, NO: +29.6 to -77.3, CO: -64.8 to -29.8, O ₃ : +31.5 to -4.3
Pei et al. (2020)	China (Beijing, Guangzhou, Wuhan,)	Air quality monitoring station data	Same period in 2019	NO ₂ : -(28.0 to 57.0)
Resmi et al. (2020)	India (Kannur)	Air quality monitoring station data	Pre-lockdown (1-24 March and 10-17 May 2020)	O ₃ : +22.0, PM ₁₀ : -61.0, PM _{2.5} : -53.0, NO: -61.0, NO ₂ : -71.0, CO: -67.0, SO ₂ : -62.0, NH ₃ : -13.0, VOCs: -61.0
Sathe et al. (2021)	India (Bengaluru, Chennai, Delhi, Kolkata, Mumbai, Pune)	Air quality monitoring station data	Same period in 2017-2019	PM ₁₀ : -24 to -62, PM _{2.5} : -42 to -60, O ₃ : -22 to -56, CO: -16 to -46, NO: -52.6 to -70.7, NO ₂ : -46 to 61
Sicard et al. (2020)	France (Nice), Italy (Rome), Italy (Turin), Spain (Valencia), China (Wuhan)	Air quality monitoring station data	Same period in 2017-2019	O ₃ : +2.4 to +36.4, PM ₁₀ : +1.8 to -48.7, PM _{2.5} : +10.6 to -36.3, NO: -52.6 to -70.7, NO ₂ : -30.4 to -69.0
Siciliano et al. (2020a)	Brazil (Sao Paulo, Rio De Janeiro)	Air quality monitoring station data	16 Feb to 15 March 2020	PM ₁₀ : +20.7 to -37.7, NO ₂ : -14.5 to -41.8, CO: -30.0 to -100
Siciliano et al. (2020b)	Brazil (Rio De Janeiro)	Air quality monitoring station data	Before partial lockdown (1 to 22 March 2020)	O ₃ : +0.1 to +12.9 NO _x : -9.2 to -48.1 NMHC: 0 to -25
Son et al. (2020)	USA (10 states)	Air quality monitoring station data	30 days before the emergency declaration date	PM _{2.5} : -4.3 to -45.1
Stratoulis and Nuthammachot (2020)	Thailand (Hat Yai)	Air quality monitoring station data	Pre-lockdown (1 Dec 2019 to 31 May 2020)	PM ₁₀ : -22.9, PM _{2.5} : -21.8, NO ₂ : -33.7, CO: +9.9, O ₃ : -12.5
Tobías et al. (2020)	Spain (Barcelona)	Air quality monitoring station data	Pre-lockdown (14 to 30 March 2020)	PM ₁₀ : -31.0 to -27.8, BC: -45.4, NO ₂ : -47.0 to -51.4, SO ₂ : -19.4 to +1.8, O ₃ : +28.5 to +57.7 NO ₂ : -22.0 to -57.0
Vadrevu et al. (2020)	India (41 cities)	Remote sensing data (Copernicus Sentinel-5)	Pre-lockdown (1 Jan to 24 March 2020)	NO ₂ : -19.0 to -13.0
Wang et al. (2020a)	China (Beijing, Chengdu, Shanghai, Xi'an, Shenzhen, Wuhan)	Remote sensing data (Copernicus Sentinel-5) Air quality monitoring station data and Random forest models	Scenario without lockdowns	PM _{2.5} : -(1.5 to 42.1), NO ₂ : -(36 to 53), O ₃ : -0.9 to +20.6, CO: -(14.5 to 28.8)
Wang et al. (2020b)	Northern China (30 Cities)	Air quality monitoring station data	Prior control period (1 to 23 Jan 2020)	O ₃ : +51.0, AQI: -20.0, CO: -20.0, SO ₂ : -16.0, NO ₂ : -54.0, PM _{2.5} : -21.0, PM ₁₀ : -27.0
Zhu et al. (2020)	Singapore	Air quality monitoring stations and Satellite data (Sentinel-5P)	Same period in 2016-2019	O ₃ : +18.0, PSI: -19.0, PM ₁₀ : -23.0, PM _{2.5} : -29.0, NO ₂ : +54.0, CO: -6.0, SO ₂ : -52.0

air pollutants such as O₃, secondary inorganic aerosol (SIA) and secondary organic aerosol (SOA) during lockdowns should also be considered (Huang et al., 2021a; Kroll et al., 2020; Sun et al., 2020).

This fundamental understanding in the formation of secondary air pollutants based on atmospheric observations in conjunction with the use of chemical transport models is important in the context of formulating air pollution mitigation policies (Chang and Hanna, 2004). For example, Sharma et al. (2020) demonstrated an overall decline of 43% in PM_{2.5} during part of the lockdown period for 22 cities in India (16 March–14 April 2020), when compared with the same time period in the previous years 2017–2019, based on modelling simulations. Miyazaki et al. (2020) provided insights into the reduction of NO_x emissions by 36% on average in Chinese provinces during the lockdown compared to the 15-year pre-lockdown period (2005–2019) using a chemical transport model. The reduced precursor (NO_x) emissions helped to explain the increased surface O₃ (+16 ppb) and the decreased PM_{2.5} (by up to 23 µg/m³) concentrations nationwide.

The factors discussed above that are related to urban air quality are thought to be responsible for large variations in the concentrations of criteria air pollutants shown in Table 1. Selected comprehensive air quality studies included in Table 1 are discussed here to provide insights into changes in OAQ in 2020. Bekbulat et al. (2021) assessed the long-

term and seasonal changes in PM_{2.5} levels (530 air quality monitoring stations across the USA) and O₃ (611 air quality monitoring stations across the USA) based upon quality-assured data collected by the US-EPA (Environmental Protection agency) during “pre-COVID” and “post-COVID” in 2020 and compared these data to those obtained from the same time periods between 2010-2019 (termed as “expected concentrations”). The levels for PM_{2.5} for all stations during post-COVID response were on average higher (3%) and those for O₃ lower (4%) compared to expected levels. The authors ascribe the relatively small but unexpected changes in PM_{2.5} and O₃ to non-linear atmospheric chemistry, resulting in complex chemical reactions involving NO_x and VOCs under clear skies. Kumar et al. (2020) used hourly PM_{2.5} data collected from five major cities in India (Chennai, Delhi, Hyderabad, Kolkata and Mumbai) to evaluate the changes in PM_{2.5} during the lockdown period compared to previous years. The PM_{2.5} data obtained in 2020 were compared to those collected during similar time periods over the past five years (2015–2019). This comparative evaluation revealed substantial reductions in PM_{2.5} concentrations, from 19 to 43% (Chennai), 41–53% (Delhi), 26–54% (Hyderabad), 24–36% (Kolkata), and 10–39% (Mumbai). In general, cities with larger traffic volume reductions showed greater decreases in PM_{2.5} concentrations. In addition to ground-based measurements of PM_{2.5}, Kumar et al. (2020) used satellite

imagery collected over the entire country to investigate the changes in Aerosol Optical Depth (AOD) which exhibited similar trends as $PM_{2.5}$. Furthermore, the authors also carried out health and related economic impact assessments which indicated 630 prevented premature deaths during the lockdown across all five cities, valued at 0.69 billion USD.

Among all the criteria air pollutants, PM and O_3 were observed to have the lowest percentage reductions (see Table 1) with some studies even reporting increases during the lockdown period for PM (Bekbulat et al., 2021; Siciliano et al., 2020a) and O_3 (e.g., Kanniah et al., 2020; Sicard et al., 2020). $PM_{2.5}$ and O_3 concentrations are influenced by complex non-linear atmospheric formation processes, which will be discussed in further detail in the following two sections. An in-depth discussion regarding the variations of these two pollutants and associated factors is needed as they are both toxic and can cause adverse health effects when inhaled at elevated levels (Chowdhury et al., 2018; Kroll et al., 2020; Nuvolone et al., 2018; Sun et al., 2020). Other than the criteria air pollutants, decreases in the concentration of black carbon (BC) (Hudda et al., 2020; Tobías et al., 2020), ammonia (NH_3) (Mahato et al., 2020; Resmi et al., 2020) and VOCs (Resmi et al., 2020; Siciliano et al., 2020b) were also observed in cities. However, studies dealing with changes in the concentrations and source variations of NH_3 are limited compared to those on SO_2 and NO_x . Concentrations of NH_3 were observed to decrease by up to 13% during the COVID-19 lockdowns. The decrease was attributed to reduced traffic and industry-related activities (Mahato et al., 2020; Resmi et al., 2020). In contrast, Zhang et al. (2021) found an increase in NH_3 levels in Beijing, China and attributed this enhancement to a shallow boundary layer rather than changes in the emission intensity of NH_3 . The conversion of NH_3 to ammonium (NH_4^+) in the particle phase is influenced by meteorological factors (temperature and relative humidity) and concentrations of acidic gases (total nitrate ($HNO_3+NO_3^-$) and total sulfate ($SO_2+SO_4^{2-}$)) (Baek et al., 2004; Behera et al., 2013). While a decrease in particulate-bound NH_4^+ was observed in studies dealing with the chemical composition of PM (Chen et al., 2020a; Sun et al., 2020), the role of NH_3 in gas-to-particle conversion has not been reported. The reduced emission of BC appears to be mainly related to a decrease in local traffic emissions, especially from diesel-powered vehicles (Hudda et al., 2020). BC is not only a toxic pollutant, but also an important contributor to global warming (Adam et al., 2020).

2.2. Impact of lockdown measures on PM

PM affects atmospheric visibility leading to haze, induces adverse human health effects and contributes to global climate change (Andreae and Crutzen, 1997; Lelieveld et al., 2015; Pöschl, 2005; Ramanathan and Carmichael, 2008). As can be seen in Table S1, only few studies have addressed the changes in PM composition, sources, and evolution processes between lockdown and non-lockdown periods. Without these insights into PM characteristics, it is difficult to formulate future PM mitigation strategies that aim at protecting human health (Lelieveld et al., 2015). Compared to other criteria air pollutants, PM exists in various sizes (from ~ 3 nm to $10 \mu m$) and is composed of primary (e.g., BC, trace elements, and crustal matter) and secondary chemical components including SOA and SIA (NH_4NO_3 , NH_4Cl , and $(NH_4)_2SO_4$) formed in the atmosphere through complex chemical reactions (Pöschl, 2005; Seinfeld and Pandis, 2016).

While time-integrated measurements are widely conducted to study the chemical composition of PM (Adam et al., 2021b; Balasubramanian et al., 2003; Betha et al., 2013; See et al., 2007a; See et al., 2006; Tran et al., 2020a), real-time measurements of PM chemical components are relatively scarce, especially during the lockdowns. High-resolution aerosol mass spectrometer (AMS)-based measurements provide a means to quantify the chemical composition of PM of various sizes ranging from 10 nm to $10 \mu m$ (Canagaratna et al., 2007; Jayne et al., 2000). The OA component can make up a large fraction ($\sim 50\%$) of PM consisting of primary organic aerosol (POA, direct emissions) and SOA

(formed from VOC oxidation, see Fig. 2a) (De Gouw and Jimenez, 2009; Hallquist et al., 2009; Jimenez et al., 2009). Recent toxicological studies demonstrated the oxidative and inflammatory potency of SOA in human lung epithelial cells and macrophages, underscoring the importance of carrying out the detailed chemical speciation of PM (Chowdhury et al., 2018; Decesari et al., 2017; Ito et al., 2019). In this review, we brought together most of the published studies reporting AMS data-based observations of PM chemical composition, which are primarily from China as can be seen in Table S1.

In general, real-time PM chemical composition measurements conducted in China indicate that the observed concentration trend of secondary aerosols was not consistent with that of primary aerosols, which decreased in response to strict lockdown measures imposed over the entire country. The key observations of changes in the PM chemical composition in China are discussed below. Sun et al. (2020) studied the lockdown effects on PM concentration and composition in Beijing, China, based on the PM data collected from 2012–2020 using quadrupole aerosol chemical speciation monitor (Q-ACSM, 2012, 2013, 2015, 2018), Time-of-Flight (ToF) ACSM (2019–2020) and Aethalometer AE22/AE33 (BC). Their findings indicate that primary PM species, which were linked to traffic, cooking and coal combustion emissions, were reduced by 30–50% on average during the Chinese New Year (CNY) period from 25 January to 2 February. However, SIA and SOA exhibited significant increases by 60–110% and 52–175%, which were attributed to regional transport of air masses from the south and the east in China and enhanced secondary aerosol formation.

Zheng et al. (2020) carried out hourly observations of $PM_{2.5}$ chemical compositions including water-soluble ions (WSIs), trace elements (TEs), organic carbon (OC), and elemental carbon (EC) in Wuhan, China, using online instruments from 23 January 2020 to 22 February 2020. They contrasted the $PM_{2.5}$ chemical speciation data observed during this time period with those during the same time period in 2019. The authors observed reductions in the concentrations of TEs and EC by about 1% during the lockdown period, suggesting little reductions in primary anthropogenic emissions of PM, while mass percentages of secondary species OC (+2.5%) and SIA (+8.7%) increased. Chang et al. (2020) performed comprehensive $PM_{2.5}$ measurements together with the use of a chemical transport model at multiple sites in China (focused on Shanghai, besides Beijing, Jiaying, Nanjing). They acquired observational data from several instruments including MARGA (semi-continuous Monitoring device for Aerosols and Gases in ambient Air), ToF-ACSM, semi-continuous OC-EC analyzer and multi-metal monitor (19 trace elements). The goal of this study was to study the impact of lockdown measures on PM characteristics in 2020 compared to 2019. While SOA levels were similar for both years, the authors noted higher levels of SIA (1.6 higher) for New Year Holiday (NYH) in 2020 compared to NYH-19 in spite of reductions in the emission of corresponding precursor species levels. This work suggested that differential transport patterns of polluted air masses, rather than local emissions of PM, might be the reason for the observed differences in $PM_{2.5}$ mass concentrations and speciation in Shanghai between NYH-20 and NYH-19. In another study in Shanghai, China, Chen et al. (2020a) contrasted ToF-ACSM-based observations of $PM_{2.5}$ speciation collected for three time periods. The authors reported that the strict quarantine measures led to lower $PM_{2.5}$ levels, which was attributed to a combination of lower primary $PM_{2.5}$ emissions and lower levels of NO_3^- formed as a result of reduced NO_x emissions. Further reductions in $PM_{2.5}$ were inhibited by increased contributions of SO_4^{2-} and SOA.

2.3. Impact of lockdown measures on O_3

Surface O_3 is formed photochemically through a series of chemical reactions involving gaseous precursors NO_x and VOCs (Sillman, 1999) as shown in Fig. 2b. VOCs are emitted from biogenic (natural wetlands, trees) and anthropogenic (fossil-fuel-related, rice paddies, landfills and biomass burning emissions) sources (Di Carlo et al., 2004; Kansal, 2009)

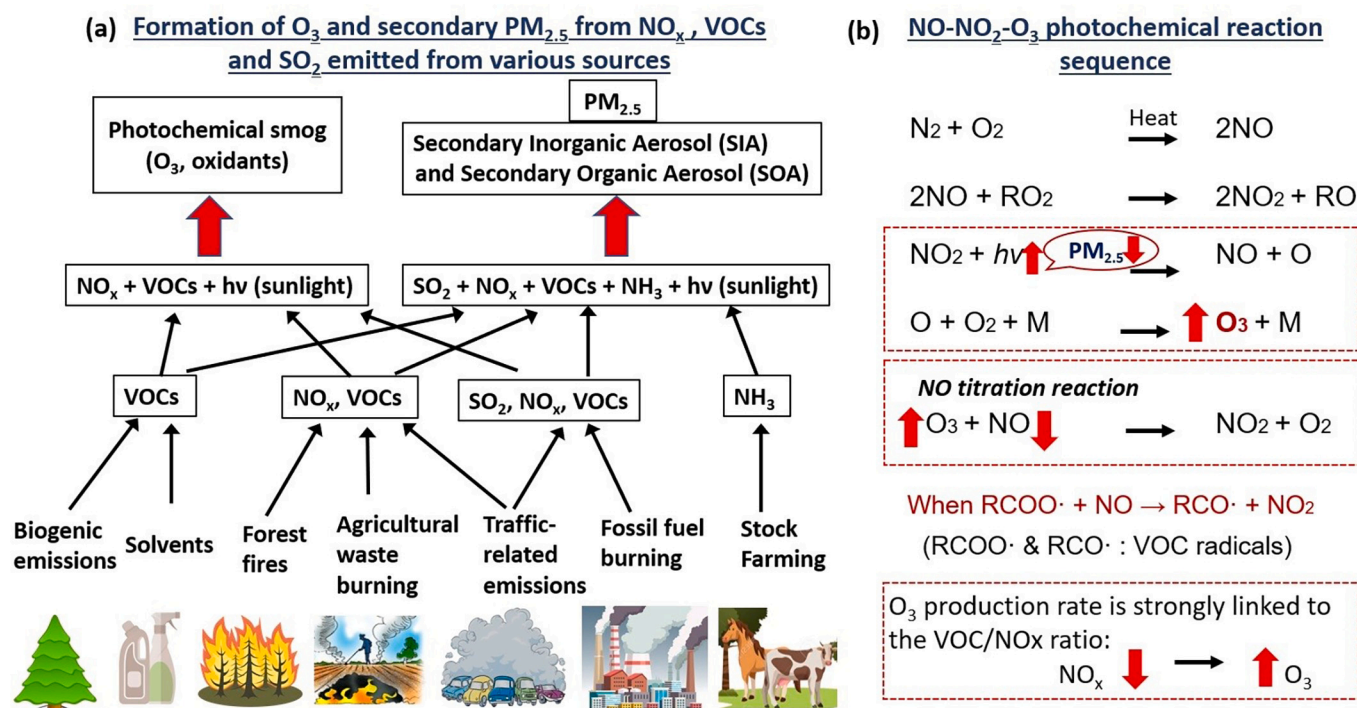


Fig. 2. (a) Formation of O₃ and secondary PM_{2.5} from various sources (adapted from Akimoto (2019)) and (b) NO-NO₂-O₃ photochemical reaction sequence.

with important implications for atmospheric chemical transformations (Atkinson, 2000). In contrast to the other air pollutants, O₃ was reported to have remained at a similar level or even show enhancements compared to pre-lockdown periods (e.g., Collivignarelli et al., 2020; Dantas et al., 2020; Nakada and Urban, 2020; Siciliano et al., 2020b; Tobías et al., 2020). Several factors may have contributed to the counter-intuitive trend of increased O₃ levels: (i) At the city-scale, the O₃ production rate is strongly linked to the VOC/NO_x ratio (Pusede and Cohen, 2012). Generally, urban areas are characterized by a low VOC/NO_x ratio due to high NO_x concentrations driven by emissions from vehicles (Sillman, 1999). However, due to the decrease in NO_x emissions from its main source (transport), it is plausible that O₃ generation was enhanced because of a high VOC/NO_x ratio and its reduced loss through the chemical titration with NO (Huang et al., 2021b). (ii) The decrease in observed PM_{2.5} levels may lead to an increase in the incoming solar radiation and thus enhanced photochemical production of O₃ (Jia et al., 2017; Wang et al., 2020a). (iii) Also, the lower PM_{2.5} levels present a less efficient sink for hydroperoxyl radicals (HO₂), enhancing O₃ generation via the peroxy radical pathway (Sicard et al., 2020).

Sicard et al. (2020) investigated changes in tropospheric O₃ levels at four European cities (Nice, Turin, Rome, Valencia) and Wuhan (China). The key findings are that the daily O₃ mean concentrations increased at the urban stations by 24% in Nice, 27% in Turin, 14% in Rome, 2.4% in Valencia and 36% in Wuhan during the lockdown in 2020. The increase in O₃ concentrations is mainly attributed to the unprecedented reduction in NO_x emissions. The other key findings are: (i) the reduction in PM levels was much smaller in Europe (~8%) than in Wuhan (~42%); (ii) the NO_x concentrations were lower in all cities during the lockdown (~49%) than those of the previous years; and (iii) the lockdown effect on O₃ production was much higher in Wuhan (38%) than in southern Europe (~10%).

Le et al. (2020) studied changes in air quality (PM_{2.5}, O₃, SO₂, NO₂) in China during the lockdown period (23 January–13 February 2020) compared to those in the previous 5 years (2015–2019). Based on the synergistic observational and model analysis, the authors concluded that nonlinear formation pathways and the lack of titration of O₃ in winter with reduced NO resulted in the enhancement of surface O₃ in urban

areas. Additionally, the oxidation capacity of the atmosphere was enhanced, which promoted the SOA formation. Liu et al. (2020a) investigated the impacts of changes in anthropogenic emissions and prevailing meteorology on the levels of PM_{2.5} and O₃ for four cities (Shanghai, Nanjing, Hangzhou, and Hefei) in the Yangtze River Delta (YRD), China, using the Community Multiscale Air Quality (CMAQ) model from 29 December 2019 to February 29, 2020. A decrease was observed in PM_{2.5} (-53% to -31%). In contrast, for O₃, significant increases were observed (+31% to +88%). The authors found that the O₃ increase was primarily driven by both emission reductions of NO_x (+29% to +52%) and variations in meteorological conditions (+17% to +49%) in YRD. The authors highlighted that strategically designed multi-pollutants (including NO_x, VOCs, and primary PM) emissions control strategies are needed to achieve a significant improvement in urban air quality.

Changes in the levels of O₃ also have implications for the oxidation capacity of the atmosphere. The oxidation capacity refers to the atmosphere's ability to degrade inorganic and organic pollutants of anthropogenic and natural origins through reactions with the atmospheric oxidants such as the hydroxyl radical (OH), O₃ and the nitrate radical (NO₃) (Monks, 2005). Tropospheric O₃ is also the dominant source of OH radicals, the key oxidant in the atmosphere during daytime (Berresheim et al., 2014; Berresheim et al., 2013). The OH radical initiates many oxidation reactions in the troposphere, leading to the formation of O₃. An increase in O₃ could in turn lead to an unintended enhancement of secondary PM_{2.5} as O₃ can also enhance the formation of SOA as shown in Fig. 2a, which has implications for environment, health and climate (Chowdhury et al., 2018; Ito et al., 2019; von Schneidmesser et al., 2015). This observation has been discussed in a few studies (e.g., Huang et al., 2021b; Jia et al., 2020; Le et al., 2020). Overall, all these studies highlight that the mitigation of secondary air pollutants such as O₃, SIA, and SOA in cities will remain a challenge even after implementation of effective policies for reduced emissions of primary air pollutants.

2.4. Impact of OAQ on COVID-19 outbreaks

There is a growing concern that air pollution may contribute to the severity of COVID-19 in persons who have contracted the virus by directly affecting the lungs' ability to clear pathogens and indirectly by exacerbating underlying cardiovascular or pulmonary diseases (Brandt et al., 2020; Comunian et al., 2020). Similar concerns were reported during the SARS (Severe Acute Respiratory Syndrome) epidemic, caused by a virus genetically identical to COVID-19, whereby high mortality rates were noted in areas with deteriorated air quality (Cui et al., 2003).

Several studies have explored the association between outdoor air pollution and severity of COVID-19 infection and mortality, and suggested that poor OAQ has the potential to increase the lethality of COVID-19 (Conticini et al., 2020; Setti et al., 2020; Wu et al., 2020; Zhu et al., 2020). These studies accounted for variations in confounding factors such as population density, socioeconomic status and meteorological variables. In an ecological regression analysis study with data from 3089 counties across the USA representing 98% of the country's population, Wu et al. (2020) found that a $PM_{2.5}$ increase of only $1 \mu\text{g}/\text{m}^3$ was associated with an 8% increase in the COVID-19 death rate. Yao et al. (2020b) used publicly available data in China (Wuhan) on PM levels and the occurrence of COVID-19 cases, and found a strong positive association between case fatality rate (CFR) and exposure to high levels of PM_{10} and $PM_{2.5}$. The authors suggest that exposure to high levels of PM increases systemic inflammation and oxidative stress in COVID-19 patients, which would in turn decrease cardiopulmonary functions. However, no attempts were made to characterize PM chemical speciation or provide details on the history of patients' prior PM exposure, age and pre-existing health conditions. Han et al. (2020) showed that higher levels of outdoor air pollution are associated with an increased COVID-19 infection rate in Wuhan, China. A generalized additive model study by Zhu et al. (2020) suggested that even short-term exposure (e.g., two weeks) to PM_{10} , $PM_{2.5}$, O_3 , and NO_2 was associated with a higher number of daily confirmed COVID-19 cases. Italy, in particular the northern region, proved to be one of the early epicentres of COVID-19 infections in the world during the spring of 2020. The region in northern Italy is generally characterized by high $PM_{2.5}$ and PM_{10} levels, and is recognized as one of the most polluted areas in Europe (Conticini et al., 2020). Two cities in the north, Bergamo and Milan, were severely affected by the outbreak of COVID-19 (Setti et al., 2020). Contini and Costabile (2020) and Conticini et al. (2020) suggested that elevated air pollution levels in northern Italy contributed to the pronounced number of COVID-19 infections and high mortality. However, their conclusions were driven based upon existing findings in the air quality and human health domain. Further experimental and epidemiological studies are urgently needed to evaluate the role of the air pollution in COVID-19 pandemic.

O_3 , NO_2 and transition metals in $PM_{2.5}$ and UFPs are potent oxidants that are able to generate reactive oxygen species (ROS) which can induce adverse human health effects via inflammation and oxidative stress (Lodovici and Bigagli, 2011; Øvrevik et al., 2015; See et al., 2007b). However, compared to traffic-related emissions of primary aerosols, the role of secondary aerosols in contributing to negative health impacts is much less understood (Adams et al., 2015a).

Limited studies have been conducted to quantify health benefits associated with strict lockdown measures imposed in polluted cities such as reduced road traffic, telecommuting and mandatory wearing of face masks. Han and Hong (2020) used publicly available data ($PM_{2.5}$ concentrations and the local population) in Seoul (South Korea) from 2016–2020 (January to April) to estimate mortality rates in 2019 and 2020. While no strict lockdown was imposed in South Korea during the study period, the $PM_{2.5}$ levels decreased by $4.1 \mu\text{g}/\text{m}^3$ in 2020 in Seoul compared to the previous 4 years. The lower $PM_{2.5}$ concentration in 2020 was attributed to two factors: (i) reduced domestic emissions of $PM_{2.5}$ due to social distancing and increased telecommuting in Seoul and (ii) lower long-range transport of $PM_{2.5}$ from China due to the

implementation of stringent lockdown measures. Overall, 38 non-accidental, 7 cardiovascular, and 5 respiratory mortalities were avoided in 2020 due to exposure to lower $PM_{2.5}$ levels. The number of estimated mortalities further decreased by a factor of 2.5 while considering the benefits of wearing face masks. This study has clearly shown the combined health benefits of reduction in $PM_{2.5}$ concentrations and positive changes in the social behavior of the public. Nie et al. (2021) reported that the reductions of PM_{10} , $PM_{2.5}$ and NO_2 levels observed in 31 provincial cities in China resulted in significant health benefits, i.e., total avoided premature deaths of 9410 (7273–11,144). NO_2 reduction was the largest contributor (55%), followed by and PM_{10} (23.9%) and $PM_{2.5}$ (10.9%). Mitze et al. (2020) used data on face masks for 401 regions (municipal districts) in Germany to study to what degree face masks protect the person using it from contracting COVID-19. The authors pointed out that face masks became mandatory at different times across Germany and found that 20 days after implementation of this mandatory requirement, the number of new infections was reduced by 45% (Mitze et al., 2020).

3. Factors affecting IAQ and their impacts

3.1. Overview of IAQ studies

As people spend the majority of their time indoors (up to 90%, (Klepeis et al., 2001; Matz et al., 2015)) and almost 100% during the lockdown, indoor air pollution (IAP) deserves more attention from human health considerations than outdoor air pollution. Although outdoor air pollution can migrate into indoor environments through advection via open windows and infiltration otherwise, there are distinct and important sources of IAP such as cooking, smoking, home cleaning and incense burning (Balasubramanian and Lee, 2007; See and Balasubramanian, 2006; See and Balasubramanian, 2008; US EPA, 2020b). Therefore, reduction of ambient air pollution is not likely to result in a similar drop in IAP (illustrated in Fig. 3) (Du and Wang, 2020). Indoor air pollutants of concern include $PM_{2.5}$, UFPs, polycyclic aromatic hydrocarbons (PAHs), VOCs, CO, NO_x , airborne microbes, and other toxic organic compounds, which can emanate not only from a range of sources as mentioned earlier, but also from emissions from

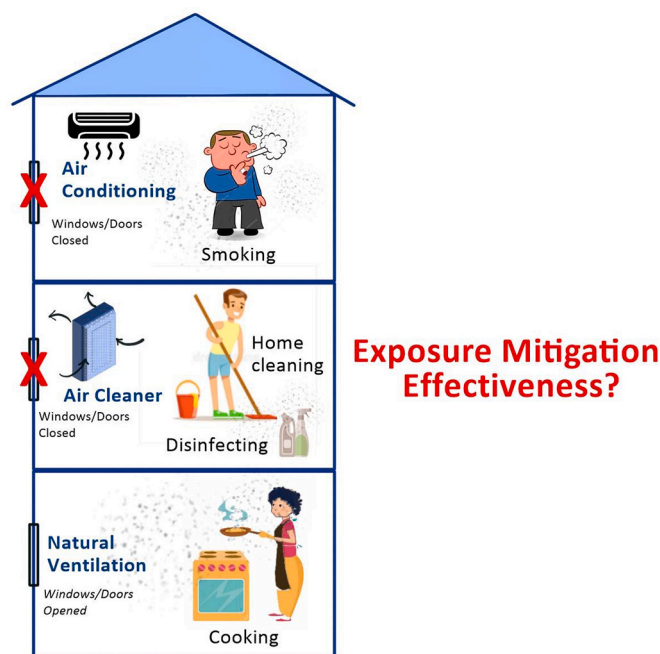


Fig. 3. Schematic of indoor air pollution and different ventilation and mitigation scenarios.

building materials or furnishings (Chakraborty et al., 2014; Gordon et al., 2014; Lewtas, 2007; Wang et al., 2017). Reactive air pollutants can be an additional source of harmful secondary indoor air pollutants, such as O₃, OH[•] radicals, nitrous acid (HONO) and VOCs (Weschler and Carslaw, 2018).

Among the aforementioned indoor air pollution sources, cooking has been identified as one of the major sources of indoor PM, especially UFPs, which are a by-product of gas-stove combustion and/or are released from food ingredients in developed countries and biomass-based cooking (Kabera et al., 2020; Pollard et al., 2014; See and Balasubramanian, 2006; Zhao and Zhao, 2018). Certain types of cooking such as deep-frying, pan-frying or roast cooking can generate elevated levels of PM_{2.5} that are similar to the concentrations observed in the world's most polluted cities (Patel et al., 2020; See and Balasubramanian, 2008; Sharma and Balasubramanian, 2020). Apart from intense and frequent cooking activities, the COVID-19 pandemic also has stimulated people to clean their homes frequently and with stronger chemicals or detergents to reduce the potential of viral infection (Anthes, 2020). Some studies have pointed out that household disinfectant products can be a significant emission source of secondary UFPs in indoor environments (Singer et al., 2006; Stabile et al., 2020). In addition, lockdown measures may result in increased levels of airborne microbes because of higher building occupant density than usual, with potential contact and airborne transmission of infectious/non-infectious microbes (Adams et al., 2015b; Kim et al., 2018). Therefore, as people are increasingly confined to their homes, population's exposure to indoor air pollutants could be expected to be elevated and prolonged, leading to increased health risks (Morawska and Cao, 2020; Nwanaji-Enwerem et al., 2020; Saha and Chouhan, 2020).

3.2. Impact of lockdown measures on IAQ

While numerous studies focused on OAQ during the COVID-19 lockdown, the number of IAQ studies are relatively scant, which are summarized in Table S2. The key outcomes of some of the studies are discussed here. A study conducted in Marid city (Spain) found that although OAQ was improved, daily indoor PM_{2.5} and TVOC (total VOC) concentrations, on average, rose by 12% and 37% to 559%, respectively, during the lockdown compared to the pre-lockdown period (Domínguez-Amarillo et al., 2020). The peaks of indoor air pollutants were associated with the period of daily cleaning and food preparation (Domínguez-Amarillo et al., 2020). These findings are consistent with those reported by Kaliszewski et al. (2020). Habitual indoor burning of incense was reported by Amatey et al. (2020) to increase indoor PM₁₀ and PM_{2.5} concentrations, facilitating the potential human to human transmission of the SARS-CoV-2 via inhalation in Middle Eastern countries. Saha and Chouhan (2020) found that children aged under-five living in indoor smoky environmental conditions in India are the most vulnerable in terms of the health risk associated with the COVID-19 disease. The risk of COVID-19 infection was estimated based on data obtained from the National Family Health Survey in India conducted with the participation of 247,743 living children and daily 'COVID-19 state-wise status' in India (Saha and Chouhan, 2020). The other vulnerable group of the general population includes smokers. A study conducted in China revealed that hospitalized COVID-19 patients with smoking behaviour were about 14 times more likely to die compared to patients who were non-smokers (Liu et al., 2020b). In addition, exposure to IAP is believed to render individuals with pre-existing health conditions and the elderly more susceptible to COVID-19 during the lockdown (Sharma and Hossain, 2020). Thakur et al. (2020) also pointed out the high susceptibility to COVID-19 infection of refugees and migrant workers staying in poor IAQ conditions.

The possible association between COVID-19 and exposure to IAP may be partly due to the influence of exposure to IAP on the respiratory and immune systems of human beings (Afshari, 2020; Saha and Chouhan, 2020; Thakur et al., 2020). Continued exposure to IAP may weaken

the human immune system, leading to decreased ability to fight against disease-causing toxicants upon inhalation. People staying in an area with high levels of indoor air pollutants are more likely to develop chronic respiratory conditions than others in relatively less polluted areas, and thus experience elevated health risk due to exposure to any infective agent (Conticini et al., 2020). The association between the exposure to IAP and respiratory ailments is thought to be due to oxidative stress, induced by PM-bound redox-active toxic elements (Cienciewicki and Jaspers, 2007; Pavagadhi et al., 2013; See et al., 2007b). Inhalation toxicology studies revealed that the exposure to PM could induce immunosuppression which in turn tends to (i) reduce the ability of macrophages to phagocytize or inactivate viruses, (ii) alter the function of surfactant proteins (SP-A and SP-D), and (iii) increase the permeability of the pulmonary epithelium. These impacts are all associated with enhanced susceptibility to respiratory virus infections (Cienciewicki and Jaspers, 2007; Tao et al., 2020). 3.8 million people a year worldwide die prematurely from illnesses attributable to household air pollution (WHO, 2020a). Poor IAQ is a long-standing public health issue and is of even greater relevance during COVID-19 pandemic (Nwanaji-Enwerem et al., 2020). Therefore, to protect human health and well-being during the COVID-19 pandemic and beyond, IAP should be prioritized and aligned with long-term environmental health initiatives on a global scale.

3.3. Impact of IAQ on COVID-19 transmission

Researchers investigated the role of various indoor air pollutants in the transmission of many infectious diseases (such as MERS-CoV, SARS-CoV-1, influenza A/H5N1) over the years. However, compared to investigations on the association between exposure to outdoor air pollution and health effects, the number of studies addressing the relationship between IAP and COVID-19 are relatively limited. A few studies have shown that occupants staying indoors with poor air quality may experience high severity of COVID-19 (Saha and Chouhan, 2020; Sharma and Hossain, 2020; Thakur et al., 2020). Also, air-tight indoor environments present a particularly conducive space for the airborne transmission of COVID-19 (Morawska et al., 2020; Velraj and Haghghat, 2020). Emerging evidence suggests that the transmission of COVID-19 via air (especially through bioaerosols) may represent an important pathway for the spread of the virus which the World Health Organization (WHO) has acknowledged in one of its latest scientific briefs on 09 July 2020 (WHO, 2020b).

Recent findings indicated a potential risk for bioaerosol (biological aerosol) transmission in the air (Kim et al., 2018; Stockwell et al., 2019). Bioaerosols are very small airborne particles (ranging in size from 0.001 to more than 100 µm) of biological origin that emanate from humans/plants/animals and can contain living organisms (e.g., viruses, bacteria, and fungi) (Douwes et al., 2003; Georgakopoulos et al., 2009). Regular human activities (e.g., breathing, talking, coughing, sneezing, walking, toilet flushing or sweeping floors) are capable of generating bioaerosols and therefore spreading pathogenic viruses (Chen and Hildemann, 2009; Cox et al., 2020). Evidence about the possibility of airborne transmission of SARS-CoV-2 is currently mounting. Several hospital-based studies have performed air-sampling, addressing COVID-19-related issues (Chia et al., 2020; Ding et al., 2020; Faridi et al., 2020; Guo et al., 2020; Jiang et al., 2020; Kenarkoohi et al., 2020; Lednický et al., 2020; Liu et al., 2020c; Ong et al., 2020; Santarpia et al., 2020). Only two of these studies (Faridi et al., 2020; Ong et al., 2020) reported the absence of SARS-CoV-2 in air samples, while the other studies found the presence of SARS-CoV-2 genome (RNA) in hospital indoor air based on polymerase chain reaction (PCR) testing. Several research studies have also highlighted that the airborne transmission of SARS-CoV-2 virus is one of the most potential modes of its infection (Anderson et al., 2020; Lewis, 2020; Morawska and Cao, 2020; Wathore et al., 2020; Zhang et al., 2020).

The small particles containing the SARS-CoV-2 virus can be spread

within indoor environments through diffusion covering distances up to 10 m from the emission sources (Morawska and Cao, 2020; Setti et al., 2020). There is a high probability of transmission of SARS-CoV-2 virus through respiratory droplets ($>5 \mu\text{m}$) and aerosols ($<5 \mu\text{m}$) emitted while speaking, in addition to coughing and sneezing (Stadnytskyi et al., 2020; Wathore et al., 2020; Zhang et al., 2020). The SARS-CoV-2 virus has been reported to be stable in the aerosol phase with a half-life of approximately 1.1–1.2 hours (Van Doremalen et al., 2020), so it can potentially be inhaled by susceptible individuals causing infection and further spreading of the disease human to human. Although airborne particles are believed to play an important role in carrying and transporting microorganisms including COVID-19, the interaction of different constituents of PM such as BC, PAHs and redox-active trace elements with coronavirus remains poorly understood due to lack of fundamental investigations addressing such interactions. In-depth studies are needed on virus survival and transmission in the presence of major individual chemical components of PM to develop a better understanding of the role of PM on the aforementioned topics.

Temperature, relative humidity and ventilation conditions are important indoor environmental factors that are related to the survival of SARS-CoV-2. Ahlawat et al. (2020) found that the chances of airborne transmission of SARS-CoV-2 are higher in dry indoor places ($<40\%$ RH) compared to humid places ($>90\%$ RH). Biryukov et al. (2020) also found that the virus decayed more rapidly when either indoor humidity or temperature remained high. Several studies have pointed out that poor ventilation in the indoor environment is associated with increased transmission of respiratory infections (Guo et al., 2021). Most COVID-19 transmission has been found to occur in indoor (or enclosed) environments particularly in crowded, poorly ventilated environments with indoor heating and doors kept closed (Miller et al., 2021), apartment building (Hwang et al., 2021), fitness centers and restaurants with minimal ventilation rate (Lu et al., 2020; Nishiura et al., 2020). In addition, recent evidence has shown that COVID-19 transmission could occur in air-tight transport microenvironments with high occupant density such as those on buses (with centralized air conditioner and in recirculation mode) (Shen et al., 2020) or in flights (Choi et al., 2020; Khanh et al., 2020). The evidence on disease transmission, e.g., in apartments, restaurants, buses, suggests that the way buildings are designed, operated and maintained influences ventilation and therefore, transmission.

Recent studies have highlighted that proper ventilation maintained in indoor environments can contain the spread of the SARS-CoV-2 virus in indoor environments (Azuma et al., 2020; Buonanno et al., 2020; Melikov et al., 2020; Morawska et al., 2020; SinBerBEST, 2020). This finding is further supported by the scientific literature that recognizes the importance of ventilation strategies to reduce the level of IAP (Ferguson et al., 2020; Stabile et al., 2019). Increasing the ventilation rate (ACH - air change per hour) has been widely suggested to be an effective management strategy to remove exhaled virus-laden aerosols, lowering their overall indoor concentrations through dilution and thus their uptake through inhalation by building occupants (Li et al., 2005; Stockwell et al., 2019). However, specific ventilation rates that can eliminate the risk of COVID-19 transmission by airborne PM have not been reported yet. There is also a lack of systematic investigations on aerosols containing chemicals and microbes under different ventilation (i.e., natural vs mechanical (with different ACH)) and exposure conditions (with and without air purification with filter-based devices). Lelieveld et al. (2020) simulated the individual risk of a particular person being infected in four indoor environments (office, school, choir and reception) and five exposure scenarios (passive ventilation + no masks; active ventilation with outside air + no masks; active ventilation + face masks; active ventilation, high-quality masks; high-volume filtration with HEPA). The simulation results show that the most effective strategy to reduce health risk is to make use of a combination of active ventilation and wearing face masks compared to other exposure reduction scenarios. However, there are significant uncertainties (e.g., related to the infective dose and

the viral load) that may influence the results of model calculations. A detailed investigation of the influence of optimizing ventilation and exposure conditions in future simulation and experimental studies can provide science-based guidelines for mitigating the risks of COVID-19 airborne transmission.

3.4. Improvement of IAQ

Based on the aforementioned review of various studies, appropriate mitigation measures need to be considered to minimize the exposure of people remaining indoors to IAP and thus the potential spread of aerosol-mode transmission of COVID-19. In buildings equipped with mechanical ventilation systems, outdoor air supply shall be kept to the maximum setting to enhance dilution of indoor air with the fresh air of outdoor origin. Recirculation of indoor air shall be set at a minimum level and treated with high-efficiency air filters (e.g., filters with equipped with Minimum Efficiency Reporting Value (MERV) 14–16) and disinfection of indoor air with UV irradiation (Siddiqui et al., 2020). Several studies have found the presence of SARS-CoV-2 in the air within restrooms/toilets (Ding et al., 2020; Liu et al., 2020c). Therefore, the exhaust ventilation in restrooms/toilets shall always be kept on to avoid the possibility of virus transmission in this indoor environment. In common areas with a high risk of crowd gatherings, such as meeting venues or the entrance lobby in large buildings, sufficient air extraction/exhaust and ventilation openings should be in place. The association between airflows and the spread of the COVID-19 virus has been reported (Borro et al., 2021; Lu et al., 2020). Therefore, it is recommended that the airflow patterns should be taken into consideration in the occupancy layout for social distancing. If fans are used in the oscillating mode, it should be ensured that the air is not blown directly from one person to another. It is also recommended that workplaces should be arranged such that there is no person directly facing one another.

For naturally ventilated buildings, windows or doors should be kept open to allow outdoor air to flow indoors without obstacles. If the recirculation air-conditioning is used, sufficient outdoor air should be provided by keeping the windows/doors minimally open in every room. Air-conditioning can be used to provide thermal comfort, but a fairly low particle removal efficiency and high energy usage may be expected (Tran et al., 2021b). There is potential to emit elevated outdoor PM levels from power plants as carbon-intensive fuels may be used to generate more electricity to meet the increased energy demand due to operation of air-conditioning systems (He et al., 2020b). Therefore, a reduction in energy consumption should be paid attention to in the context of improving IAQ. To reduce indoor airborne particles including viruses, HEPA-based portable air cleaners (PACs), fan filters, and disinfection devices (such as germicidal ultraviolet) may be deployed (James et al., 2020; Sharma and Balasubramanian, 2017, 2019; Tham et al., 2018; Tran et al., 2021b; US EPA, 2020a). The selection of PACs depends on its performance in relation to the size of the room where it is placed; clean air delivery rate (CADR) is a very important factor to consider (AHAM, 2013; Shaughnessy and Sextro, 2006).

Viral infection largely depends on the amount of active viral inhaled dose and the immunity status of exposed individuals. To effectively minimize the exposure dose, wearing face masks is necessary, especially when staying or entering a closed environment with a high possibility of SARS-CoV-2 accumulation and transmission (Kohanski et al., 2020; Lelieveld et al., 2020; Yao et al., 2020a). However, different face masks have different protection efficiencies and degrees of fitness (Yao et al., 2020a; Zou and Yao, 2015). Several previous studies have shown that N95 and surgical masks have effectively reduced the wearer's exposure and community transmission of coronavirus and influenza viruses (Jefferson et al., 2008; Leung et al., 2020; MacIntyre et al., 2017). Face shields are also proposed as an effective way to prevent early exposure to high-velocity aerosols or droplets (generated by coughing or sneezing) before impacting on a face mask or respirator (Lindsley et al., 2014). Wearing of face masks is recommended as the most effective means to

prevent inter-human transmission, and this inexpensive practice, in conjunction with simultaneous active ventilation in indoor environments, contact tracing, quarantine and social distancing, represents the most likely fighting opportunity to stop the COVID-19 pandemic (Lelieveld et al., 2020; Zhang et al., 2020).

For maintaining an individual's immune system and ensuring long-term protection of public health, elimination or at least mitigation of the intensity of indoor air pollution sources is essential. Switching to electric appliances instead of wood or gas stoves, avoiding cooking/frying at very high temperature, and using kitchen hoods during cooking may prove to be effective in reducing the exposure to PM released from indoor cooking (Snider et al., 2018; Zhao and Zhao, 2018). When cleaning, it is good to avoid the overuse of disinfection products or chemicals that may contribute to the emission of hazardous substances to the indoor air (Nwanaji-Enwerem et al., 2020). Alternatively, the use of disinfectants that are less aggressive and have lower emissions of chemicals should be encouraged (e.g., avoiding the use of disinfectant sprays) (Domínguez-Amarillo et al., 2020).

4. Policy implications

Air quality management is a serious challenge because of the chemical complexity of outdoor and indoor air. Since anthropogenic activities are the main drivers of air pollution across the world (Fuzzi et al., 2015), policy decisions are the most effective tool to mitigate the emission of air pollutants and improve air quality for the benefit of human health and the environment. However, these decisions need to be made in accordance with a sound fundamental understanding of the science underpinning air pollution (Kroll et al., 2020). In this context, it is important for air quality scientists and policy makers to work together so that the scientific lessons learnt from air quality observations around the world during the lockdown can be translated into air pollution control policy-oriented actions. We point out several policy-oriented actions below.

4.1. Co-mitigation of PM and O₃

The central take-home lesson from the lockdowns is that future air pollution control policies need to address the co-mitigation of PM_{2.5} and O₃ pollution (see Fig. 4). However, until recently, PM_{2.5} and O₃ were treated as two separate air pollutants (Li et al., 2019). Tropospheric O₃ is formed in the atmosphere through a complex set of photochemical reactions, and poses a threat to human health when its concentration is elevated. Likewise, the formation of secondary PM containing both inorganic and organic species is very complex and depends on the oxidizing capacity of the atmosphere and meteorological conditions. Secondary PM_{2.5} contributes substantially to overall PM_{2.5} levels (Jimenez et al., 2009; Volkamer et al., 2006) and is associated with detrimental health effects (Ito et al., 2019). The synergistic health effects of PM_{2.5} and O₃ remain unknown. Compared to controlling primary

emissions of PM_{2.5}, reduction in the concentration of secondary PM_{2.5} is more challenging as its formation can occur via aqueous-phase or gas-phase photochemical processes. Given that the same gaseous precursors are involved in the formation of both O₃ and secondary aerosols, an integrated air pollution control policy is needed based on the following measures by: (i) lowering emissions of both NO_x and SO₂ from fossil fuel combustion sources in order to mitigate the formation of sulfate (SO₄²⁻) and nitrate (NO₃⁻) which are major components of SIA and to suppress the formation of O₃ as NO_x is an important precursor; (ii) lowering emissions of both NO_x and VOCs simultaneously to further reduce O₃ and decrease the formation of SOA (Akimoto et al., 2015).

Recent (2013–2017) stringent air pollution control measures implemented in China to regulate the emission of primary pollutants led to similar observations as those during the lockdowns whereby a decrease in PM_{2.5} levels had the unintended consequence of increasing O₃ levels (Li et al., 2019; Zhang et al., 2019). Atmospheric chemistry model simulations performed by Li et al. (2019) showed that the scavenging of the hydroperoxy (HO₂) and nitrate (NO₃) radicals by PM was reduced due to lower PM_{2.5} levels, resulting in enhanced O₃ formation. The authors suggest that reductions of NO_x and aromatic VOC emissions may be particularly effective for decreasing SOA and O₃ in parallel (see Section 2.3. for details on O₃ chemistry). However, the authors did not discuss potential changes in PM_{2.5} speciation in the study. Furthermore, air quality modelling studies indicate that if appropriate air pollution control policies were to be implemented for simultaneous mitigation of both PM_{2.5} and O₃, significant public health benefits could be derived. For example, population exposure to PM_{2.5} could be drastically reduced (up to 75% reduction of PM_{2.5}) by implementing anthropogenic emission reductions, bringing PM_{2.5} levels well below WHO guidelines along with a reduction in premature deaths (Amann et al., 2020). In another global atmospheric chemistry-climate model study, Lelieveld et al. (2019) showed that replacement of fossil fuels by renewable energy sources would reduce global premature deaths by 65% because of reduction in the atmospheric levels of both primary and secondary air pollutants. A combination of measurements of the changes in atmospheric chemical composition and the use of appropriate chemical-transport models will inform what policy interventions would be most effective for the co-mitigation of PM_{2.5} and O₃.

In order to mitigate the concentration of PM_{2.5} and O₃, a multi-pronged approach with the development of pro-active policies focusing on effective air pollution control at the sources of 3 their precursor species (SO₂, NO_x and VOCs) is needed. The following pollution control measures are suggested: (i) post-combustion emission controls at large plants in the power and industry sectors; (ii) effective mitigation of these precursor emissions from industrial processes, including steel, cement and glass production; (iii) implementation of higher emissions standards such as Euro VI for diesel and gasoline vehicles (Jonson et al., 2017; Rhys-Tyler et al., 2011); (iv) large-scale installation of renewable energy sources such as wind, solar and hydro power for electricity generation in countries by providing economic incentives (Alvarez-

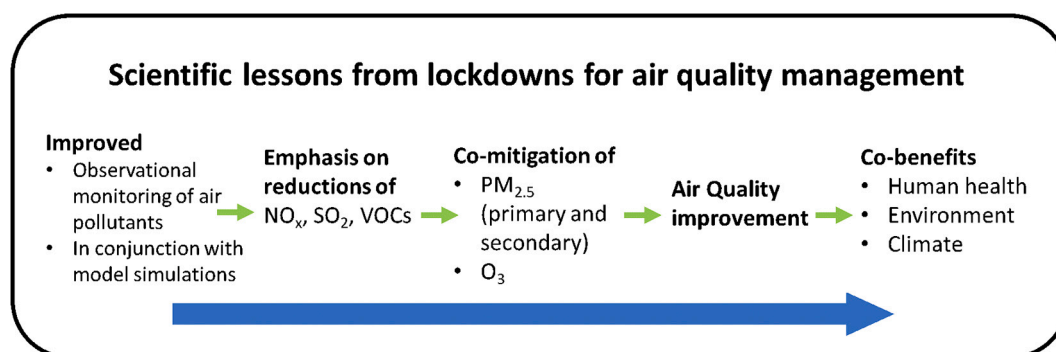


Fig. 4. Policy implications as a result of the scientific findings made during the lockdowns across the world.

Herranz et al., 2017); (v) prescribed land clearing activities associated with agricultural practices to prevent the occurrence of biomass burning episodes (forest and peat fires) (Adam et al., 2021b); (vi) the use of clean cooking fuels such as electricity and liquid petroleum gas (LPG) (Rosenthal et al., 2018); (vii) improved energy efficiency of household appliances, buildings, lighting, heating and cooling and encourage rooftop solar installations; (viii) environmentally-benign urban planning involving green infrastructure and low-emission zones in cities (Kumar et al., 2019); (ix) promotion of public and active transport and vehicle sharing concepts with the added benefits of physical activity if active transport is used (Rabl and De Nazelle, 2012; Tran et al., 2021c). To facilitate this lifestyle habit change, cities need to make appropriate changes to their infrastructure, e.g., by implementing more cycling lanes (Tran et al., 2020b); and (x) promotion of electric and fuel-cell powered vehicles in cities (Liang et al., 2019).

4.2. IAQ control

The topic of indoor air pollution merits increased attention as people spend a considerable amount of their time indoors. However, IAQ guidelines currently do not exist in many countries, but are necessary for health risk assessment (Morawska et al., 2013; Morawska et al., 2017). IAQ considerations are of particular importance to human health during lockdowns due to the intensity of human activities taking place in close proximity to indoor occupants (e.g., cleaning, cooking, smoking and incense burning) and the long duration of exposure to air pollutants (Du and Wang, 2020). Policy makers, building scientists, and air quality scientists should work together to establish specific IAQ guidelines that are relevant to individual cities by taking into consideration the local population density, demography, topography and lay-out of residential buildings. While attempting to improve IAQ, it is important to note that the continued use of various indoor appliances would lead to increased energy consumption and thus increased emissions of air pollutants including CO₂ from power plants.

4.3. Health risk assessment

Air Quality Index (AQI) that is indicative of the level of outdoor air pollution has been widely used by government agencies around the world to inform the public of potential health effects of exposure to outdoor air pollutants. However, no such index is currently available to provide health advisory. As a result, indoor occupants tend to underestimate health risk, especially while being home quarantined. If appropriate health advisory is provided, this will enable the vulnerable members of the population to make an informed decision about protecting their health against exposure to harmful indoor air pollutants by using effective exposure mitigation devices. As people are mobile, integrated air pollution exposure assessment based on the concentrations of air pollutants, particularly PM, measured in both outdoor and indoor microenvironments using portable sensors is vital (Adam et al., 2021a; Tran et al., 2021c; Tran et al., 2020a). This kind of exposure assessment will allow people to minimize health risks by avoiding visits to polluted or crowded environments. From the policy viewpoint, there is an urgent need to conduct epidemiological studies with an aim of investigating the relationship between time-integrated exposure to air pollution across both outdoor and indoor microenvironments and health impacts associated with COVID-19. Spatiotemporal variations of air pollutants and exposure assessment models should be coupled to develop appropriate pro-active policies in the context of mitigation of health risk (Stewart et al., 2017; Vitolo et al., 2018).

According to the WHO, more than 90% of urban dwellers are subject to air quality levels above the WHO issued global air quality guideline value for PM_{2.5} in ambient air of 10 µg m⁻³ as annual mean (WHO, 2018). However, the total PM mass concentrations may not be an appropriate indicator of its health impacts as the different PM chemical components have differing toxicological potential (Betha et al., 2014;

Pavagadhi et al., 2013; Wu et al., 2017). Hence, health impact assessments of PM should consider its chemical composition (Betha et al., 2014; Betha et al., 2013).

5. Summary and recommendations

The lockdowns imposed by governments around the world in response to the steep surge in COVID-19 infections in early 2020 provided a unique opportunity to enhance our understanding of how anthropogenic activities impact air quality based on the reconstruction of knowledge generated by the scientific community out of the global-scale experiment conducted in the natural laboratory. While the approach to study the changes in air quality during the lockdown compared to pre- and post-lockdown periods varied among researchers, most countries in general reported a substantial decline in the levels of primary air pollutants including NO_x, SO₂, and CO, and primary PM, which was largely attributed to reductions in traffic-related emissions and some industrial emissions. However, the complex and nonlinear response of secondary chemical components of PM to air pollution control measures meant that the formation of secondary PM at least partially offset the reductions in primary PM. Furthermore, most studies reported either minimal to no reduction, or even an increase in surface O₃ concentrations. Compared to OAQ studies, IAQ investigations were relatively scarce in spite of the global population spending the majority of their time indoors during the lockdowns, accompanied by pollution-causing household activities such as cooking and cleaning. In the context of human health considerations, studies have shown that the airborne transmission of the SARS-CoV-2 virus, particularly in indoor environments, is of serious concern. Specifically, high levels of air pollution can exacerbate the human health impacts that COVID-19 patients experience and slow down their recovery. For transmission of the virus, it is important how indoor environments (i.e., buildings) are designed, operated and maintained because of the influence of ventilation the transmission of airborne virus. The consolidation of key findings on OAQ and IAQ has important implications for development and implementation of air pollutant control strategies. Concerted efforts are needed to phase out anthropogenic emissions from carbon-intensive sources through implementation of pro-active policies, aiming at co-benefits in terms of better OAQ & IAQ, improved human health and climate resilience.

Major recommendations arising from this critical review are listed below:

- The enhanced formation of secondary PM_{2.5} and O₃ under favorable pollution and weather conditions indicates that an integrated air pollution control policy is needed for the co-mitigation of both PM_{2.5} and O₃ with the use of an appropriate chemical transport model.
- Fundamental multi-disciplinary scientific investigations are needed to provide insights into the interplay of anthropogenic emissions of air pollutants, prevailing meteorology and atmospheric chemistry in the context of developing urban air quality management strategies.
- Observational air pollution data obtained from multiple platforms should be analyzed to identify temporal and spatial distributions of primary and secondary air pollutants in conjunction with the use of chemical transport models and source apportionment techniques.
- Assessment of air quality in indoor environments, especially in domestic environments, is of great significance during lockdowns as people spend most of their time indoors, being exposed to air pollutants of diverse origins including indoor activities. However, studies investigating changes in IAQ are scarce. Such studies should be conducted under different ventilation conditions and occupancy levels and with exposure mitigation technologies to assess and manage human health risk so that appropriate IAQ guidelines can be recommended.
- High levels of outdoor and indoor air pollution can potentially aggravate the adverse health impacts that COVID-19 patients might

experience and slow down their recovery. Hence, an integrated assessment of OAQ and IAQ using mobile devices is warranted.

- There is a lack of epidemiological investigations and *in vivo* and *in vitro* studies to investigate potential health impacts of infectious aerosols in the presence of PM and other air pollutants in the background outdoor/indoor air. Such investigations are needed to formulate effective strategies to improve air quality.
- Clean air policy development, focused on the decarbonization of economies with the integration of transport, industrial and energy sectors, is necessary to bring a paradigm shift in how air pollution challenges are tackled in the future while the global population and urbanization are on the rise.

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Appendix A. Supplementary data

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