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Critical assessment of restrictive socioeconomic measures taken during the SARS-CoV-2 pandemic and their impact on air quality worldwide

Avaliação crítica das medidas socioeconômicas restritivas adotadas durante a pandemia de SARS-CoV-2 e seu impacto na qualidade mundial do ar

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ABSTRACT

The ongoing global pandemic of the coronavirus disease 2019 has been a public health emergency of international concern. Countries have adopted several restriction measures. Because of this fateful moment, it was possible to assess the effect of anthropogenic activities on air pollutants in an unprecedented way. This work aims to outline changes in the air quality levels of several cities worldwide after the COVID-19 pandemic. Data on the criteria pollutants found in these cities before and during the pandemic were used to evaluate air quality performance. The collection of most of the data was possible thanks to the constant monitoring methods applied in some countries. The severe limitation of people's movements significantly reduced pollutants concentration, mainly due to the traffic of vehicles. Carbon monoxide, sulfur dioxide, nitrogen dioxide, particulate matter 2.5 µm, and particulate matter 10 µm (CO, SO_2, NO_2, $PM_{2.5}$, and PM_{10}) concentration reductions were observed due to more restrictive or flexible lockdowns. In almost all cities evaluated, WHO's air quality guidelines have been achieved, except for tropospheric ozone, which has been increasing with the reduction of nitric oxides (NOx) emissions. The increment in the concentrations of the pollutants immediately after the end of the restrictions is an indication that control strategies must be implemented to improve air quality.

Keywords: criteria pollutants; lockdown; vehicle emission; social distancing.

RESUMO

A pandemia global em curso da doença de coronavírus 2019 tem sido uma emergência de saúde pública de interesse internacional. Os países adotaram várias medidas de restrição. Este momento fatídico permitiu avaliar o efeito das atividades antrópicas sobre os poluentes atmosféricos de forma inédita. Este trabalho tem como objetivo apresentar a variação dos níveis de qualidade do ar de várias cidades do mundo após a chegada da pandemia do COVID-19. Critérios de dados de poluentes dessas cidades antes da pandemia e durante seu curso foram adotados para avaliar o desempenho da qualidade do ar. A coleta da maioria dos dados foi possível graças aos métodos de monitoramento constante aplicados em alguns países. A severa limitação dos movimentos das pessoas reduziu significativamente a concentração de poluentes, principalmente em razão do tráfego de veículos. As reduções das concentrações de CO, SO_2, NO_2, $MP_{2,5}$ e MP_{10} foram observadas pelo bloqueio mais restritivo ou flexível. Em quase todas as cidades avaliadas, as diretrizes de qualidade do ar da Organização Mundial da Saúde foram alcançadas, exceto para os níveis de ozônio troposférico, que vêm aumentando com a redução das emissões de NOx. O incremento nas concentrações dos poluentes imediatamente após o fim das restrições é um indicativo de que estratégias de controle devem ser implementadas para melhorar a qualidade do ar.

Palavras-chave: critérios de poluição; *lockdown*; emissão veicular; isolamento social.

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Introduction

The COVID-19 pandemic

At the end of 2019, the first cases of pneumonia, specifically a severe acute respiratory syndrome (SARS-Cov-2) associated with a new coronavirus disease named COVID-19, were reported in Wuhan, China (Huang et al., 2020; Zhu et al., 2020). In April 2020, several cases were detected all over the world (Bontempi, 2020; Grasselli et al., 2020). Therefore, the World Health Organization (WHO) had to declare, on March 11th, 2020, that COVID-19 had become a pandemic, and it has been a public health emergency of international concern (Kumar and Morawska, 2019).

The United States (U.S.) reported the first coronavirus case on January 20th, 2020, in Washington State (Dong et al., 2020). At almost the same time, Australia recorded the first case of COVID-19 on January 25th of the same year (Dong et al., 2020). However, Latin America was free of the virus until February 2020, with the first case confirmed in Brazil on February 26th and in Argentina only on March 5th.

On March 2nd, 2020, Moroccan authorities declared a "state of health emergency" after detecting the first case of COVID-19 in the country (Maneesh and El Alaoui, 2020; El Alaoui and P 2020; Otmani et al., 2020). Therefore, the virus has spread all over the continents: Asia, Europe, America, Oceania, and Africa, as tracked in a real-time COVID-19 Map, hosted by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University, Baltimore, MD, USA (Dong et al., 2020).

The COVID-19 pandemic has substantially affected human society, including health care, economic structures, and social relationships. The lockdown response to COVID-19 has caused an unprecedented reduction in the global economic activity and a unique opportunity to estimate the short-term effects on air quality worldwide (Venter et al., 2020). Berman and Ebisu (2020) complement that understanding how air pollution is affected by extreme disruptions in anthropogenic behavior would provide key answers regarding the health and control of air pollution emissions (Berman and Ebisu, 2020).

Air pollutant criteria ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, and O_3) have severe effects on human health (GBD 2019 Demographics Collaborators, 2020). Adverse health outcomes range from increased visits to the emergency department, hospitalizations, and death from various cardiorespiratory diseases. This study investigated changes in the concentrations of the six criteria air pollutants before, during, and after the COVID-19 lockdown periods. This study aims to show, in a unique paper, the results verified by the literature about the reduction of air pollutant concentrations for some sites in the five continents before, during, and after lockdown periods to contain the spread of the COVID-19 virus, as well as the control measures adopted for each one. In addition, it aims to seek a reflection on strategies that could be maintained to reduce air pollution, given the results achieved in this fateful period, when the emission sources were strongly reduced.

Control measures in the form of social distancing

With the rapid transmission of the COVID-19 virus, many governments enforced lockdown measures to contain the spreading of the virus and encourage social distancing. Lockdown measures have included partial or complete closure of international borders, schools, universities, non-essential businesses, churches, bars, restaurants, community centers, beaches, and entertainment venues and, in some cases, restricted citizen mobility (Kumar and Morawska, 2019; Dantas et al., 2020; Leung et al., 2020; Wang and Su, 2020).

Many nations ordered a total lockdown (TL) within the city or state or in the whole country (*e.g.*, India) (Chauhan and Singh, 2020). In China, only essential enterprises involving people's immediate needs (such as health care or providing food) were allowed to operate until February 10th (Wang and Su, 2020). These measures led to a dramatic reduction in the number of vehicles on the road and a near-total reduction in factory production (Wang and Su, 2020). Therefore, economic activity has come to a near-complete standstill in many countries (Heneghan et al., 2020).

In Italy, the Government adopted, at first, a partial lockdown (PL) in most of the Northern territory, including the whole Lombardy Region, prohibiting any commuting that did not involve reaching the workplace and only essential industrial activities remained operating. After this, the country declared a TL, in which only factories working with essential supply chains (e.g., food, pharmaceuticals, etc.) were authorized to remain operative (DPCM, 2020a). Spain followed afterward, with the government introducing confinement rules on March 14th, 2020, allowing citizens to leave home only for essential trips and ordering the closure of all businesses not providing critical services during the pandemic (IQAir, 2020).

In Brazil, a PL was declared by the São Paulo and Rio de Janeiro governments in the third week of March (Dantas et al., 2020; Diário Oficial do Estado de São Paulo, 2020), with industries and civil construction operating as usual. In Morocco, all cities adopted a TL, with most industrial and commercial establishments forced to stop their activities (Maneesh and El Alaoui, 2020; Otmani et al., 2020).

In the U.S., states and municipalities have been responsible for ordering measures to contain the spread of the virus. However, in 2020, California was the first state to demand a mandatory lockdown on March 20th, ordering the closure of all non-essential services and encouraging residents to stay at home. While responses across the 50 states have varied, the majority have followed similar orders as California (IQAir, 2020).

The lockdown around the world helped to slow down the spread of the virus through containment measures that had a considerable impact on the daily life of citizens. Nevertheless, the aforementioned conditions also positively impacted air quality (Chauhan and Singh, 2020; Dantas et al., 2020; Tobías et al., 2020), considering that pollution emissions from the transportation and industrial sectors decreased (Wang et al., 2020).

Anthropogenic activities versus air quality

Particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxides (NO_2), and sulfur dioxide (SO_2) are the most common ambient air pollutants and are regulated by many countries (Martins et al., 2017). These pollutants have been emitted primarily by anthropogenic sources, such as road traffic (e.g., motor exhaust, brake and tire wear, and soil suspension) and industrial activities (e.g., metallurgy, oil refinery, and power plants) (Thorpe and Harrison, 2008; Ventura et al., 2017; Man et al., 2020). According to the WHO, 4.6 million individuals die annually from diseases and illnesses directly related to poor air quality (Cohen et al., 2017), even in developed countries, such as the European nations, where 193,000 people died in 2012 from airborne particulate matter (Ortiz et al., 2017). According to these data, the impact of air pollution is a global problem (Ortiz et al., 2017).

The COVID-19 pandemic has likely affected air quality globally due to extreme changes in human behavior (Berman and Ebisu, 2020). Recent studies have reported that air quality improvements during the outbreaks are associated with the level of lockdown implemented (Collivignarelli et al., 2020; Dantas et al., 2020; Nakada and Urban, 2020; Sharma et al., 2020; Siciliano et al., 2020; Tobías et al., 2020; Wang and Su, 2020; Zambrano-Monserrate et al., 2020). Furthermore, containment measures flattened the contagion curve of the COVID-19 pandemic around the world while also giving the opportunity to reduce displacements and minimize industrial activities in an unprecedented way, creating unique conditions for assessing the effect of anthropogenic activities on air pollutants in all the five continents (Van Donkelaar et al., 2015; Carugno et al., 2017).

A long-term global lockdown is not sustainable (Kumar and Morawska, 2019; Venter et al., 2020). However, the findings illustrate potential strategies that could be preserved to improve air quality and afford the health benefits gained from reducing some usual air pollutant emissions (Venter et al., 2020).

Methodology

As the air quality is monitored on all continents, it was possible to collect criteria pollutants (CO, NO_2, SO_2, PM_{10}, $PM_{2.5}$, and O_3) data from several cities before and during the COVID-19 pandemic. Also, the restriction measures allowed assessing the effect of anthropogenic activities on air pollutants in an unprecedented way (Collivignarelli et al., 2020; Dantas et al., 2020; Nakada and Urban, 2020; Sharma et al., 2020; Siciliano et al., 2020; Tobías et al., 2020; Wang and Su, 2020; Zambrano-Monserrate et al., 2020). However, many studies were found in the African continent (Otmani et al., 2020) and Oceania (Venter et al., 2020).

There is a diversity of ways and sampling methods to determine air pollutants, such as monitoring by satellite or surface stations, with different precision and accuracy levels (Berman and Ebisu, 2020; Dantas et al., 2020; Venter et al., 2020). Besides, each place has a pre-existing local air pollution scenario, for example, Asian countries, such as China and India, have high levels of air pollution based on the WHO guideline values (Mahato et al., 2020; Sharma et al., 2020; Wang and Su, 2020). Due to that, this study outlined the verified percentage reductions of the air quality criteria pollutants as a consequence of social distancing as a control measure, which consequently decreased emissions from different sources, especially vehicles and, in some cases, industrial activities.

Several studies argued the effect of meteorology on atmospheric concentrations (Ocak and Turalioglu, 2008; Dragomir et al., 2015). Although the meteorological parameters play a significant role in air pollution, the majority of the studies published about the quarantine period have not quantified its influence on air quality (Dantas et al., 2020; Otmani et al., 2020; Sharma et al., 2020). Nonetheless, it is well known that atmospheric processes can determine air quality concentrations and that they are nonlinear with the pollutants emission rates due to the meteorological conditions, which can be favorable or not for the air pollution levels (Ventura et al. 2017; Sharma et al., 2020; Wang et al., 2020). A summary of the different monitoring methods for the significant pollutants discussed is reported in Table 1.

Results

As a consequence of the measures and control actions undertaken to stop the spread of the COVID-19 virus, air pollution from primary anthropogenic emission sources (transportation and industrial sectors) was expected to decrease in many nations worldwide, while air quality improvement would be observed for the primary pollutants (Berman and Ebisu, 2020; Mahato et al., 2020; Otmani et al., 2020; Wang et al., 2020). Nevertheless, it would be interesting to acknowledge how much each activity contributed to that and which atmospheric pollutants were most affected.

Therefore, this section outlines the primary outcomes observed in the recent literature about the effects of the COVID-19 pandemic control measures on the primary pollutants regulated (CO, SO_2, NO_2, O_3, $PM_{2.5}$, and PM_{10}) and air quality worldwide (Table 2). It is expected to observe different air quality improvements for each city. While the cities' lockdown measures could be significantly similar, the contribution of each emission source to local air pollution is not the same (Man et al., 2020).

We did not find articles associated with the impact of the actions taken to control the spread of COVID-19 on air quality in any country in Oceania. However, through the data available on the Air Quality Index platform (IQAir, 2020), which disseminates air quality data from 388 cities around the world, it was possible to calculate the air pollutant concentration decrease in the city of Sydney, Australia, comparing the average monthly concentrations recorded in December 2019, one month before the arrival of the virus in Australia, and in February 2020, one month after a COVID-19 case was first recorded in the country.

Table 1 – Monitoring methodologies used during the pandemic to assess the main pollutants in the cited articles.

Pollutant	Methodology Used for Monitoring	Reference
CO	Based on ESA, which used the Copernicus Sentinel-5P satellite to track and observe air pollution in the atmosphere.	Wang and Su, 2020
	In China, real-time monitoring data was obtained from the CNEMC	Wang et al., 2020
	The AQI underwent revisions and the parameter INAQS was used	Mahato et al., 2020
	Air pollutant concentration data were extracted from the ARPA	Collivignarelli et al., 2020
	Data on atmospheric pollutants and climatic conditions were obtained through the automatic monitoring system of the SMAC	Dantas et al., 2020 (RJ)
	Atmospheric pollutant data from CETESB	Nakada and Urban, 2020
	Meteorological data and air pollutant concentrations were obtained from the Indian CPCB	Sharma et al., 2020
	Data on atmospheric pollutants and weather conditions were obtained through SMAC's automatic monitoring system.	Siciliano et al., 2020
NO, NO_2 NOx	The tracking and determination of NO_2 concentration in the atmosphere was made by NASA and ESA satellites	Wang and Su, 2020
	The dynamics of atmospheric NO_2 was studied by satellite data (TROPOMI instrument).	Venter et al., 2020
	US NO_2 samples were extracted from the OpenAirQuality monitoring site using the 'ropenaq' package in the R statistics program.	Berman and Ebisu, 2020
	In China, real-time monitoring data for NO_2 were obtained from the CNEMC. Geographic distributions of secondary industries and industrial NOx emissions were obtained from the 2018 China City Statistical Yearbook.	Wang et al., 2020
	ENVEA Cairpol's low-cost electrochemical sensors were used to collect high-resolution temporal data on NO_2 concentration.	Otmani et al., 2020
	NO_2 readings were taken at the Copernicus Sentinel-5P in Rome, Madrid, and Paris. [CAMS (2020)]	Zambrano-Monserrate et al., 2020
	The AQI underwent revisions and the INAQS parameter was used for NO_2	Mahato et al., 2020
	Air pollutant concentration data were extracted from the ARPA	Collivignarelli et al., 2020
	Data on atmospheric pollutants and climatic conditions were obtained through the automatic monitoring system of the SMAC	Dantas et al., 2020
	Atmospheric pollutant data from CETESB	Nakada and Urban, 2020
	Meteorological data and air pollutant concentrations were obtained from the Indian CPCB (NO, NO_2 e NOx)	Sharma et al., 2020
	Data on atmospheric pollutants and weather conditions were obtained through SMAC's automatic monitoring system.	Siciliano et al., 2020
	Meteorological data were provided by Meteocat and MITECO. Pollutant data were obtained from XVPCA	Tobías et al., 2020
SO_2	Based on ESA, which used the Copernicus Sentinel-5P satellite to track and observe air pollution in the atmosphere.	Wang and Su, 2020
	In China, real-time monitoring data for SO_2 were obtained from the CNEMC. Geographic distributions of secondary industries and industrial SO_2 emissions were obtained from the 2018 China City Statistical Yearbook.	Wang et al., 2020
	ENVEA Cairpol's low-cost electrochemical sensors were used to collect high-resolution temporal data of SO_2 concentration.	Otmani et al., 2020
	The AQI underwent revisions and the parameter INAQS was used.	Mahato et al., 2020
	Air pollutant concentration data were extracted from the ARPA	Collivignarelli et al., 2020
	Atmospheric pollutant data from CETESB	Nakada and Urban, 2020
	Meteorological data and air pollutant concentrations were obtained from the Indian CPCB	Sharma et al., 2020
	Meteorological data were provided by Meteocat and MITECO. Pollutant data were obtained from XVPCA	Tobías et al., 2020
PM_{10}	In China, real-time monitoring data was obtained from the CNEMC (http://www.cnemc.cn).	Wang et al., 2020
	PM_{10} was measured in quartz fiber filters (pre-baked) of 150 mm in diameter. Daily samples were collected with a high volume sampler for 24 h, with a flow rate of 30 m^3/h. To determine the mass concentrations of PM_{10}, the filters were weighed before and after sampling using a Mettler.	Otmani et al., 2020
	The AQI underwent revisions and the parameter INAQS was used	Mahato et al. 2020
	Air pollutant concentration data were extracted from the ARPA	Collivignarelli et al., 2020
	Data on atmospheric pollutants and climatic conditions were obtained through SMAC's the automatic monitoring system	Dantas et al., 2020
	Atmospheric pollutant data from CETESB	Nakada and Urban, 2020
	Meteorological data and air pollutant concentrations were obtained from the Indian CPCB	Sharma et al., 2020
	Data on atmospheric pollutants and weather conditions were obtained through SMAC's automatic monitoring system.	Siciliano et al., 2020
	Meteorological data were provided by Meteocat and MITECO. Pollutant data were obtained from XVPCA	Tobías et al., 2020

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Table 1 – Cotinuation.

Pollutant	Methodology Used for Monitoring	Reference
$PM_{2.5}$	The dynamics of atmospheric pollutants was studied by satellite data (TROPOMI instrument)	Venter et al., 2020
	US samples were extracted from the OpenAirQuality monitoring site using the 'ropenaq' package in the R statistics program	Berman and Ebisu, 2020
	In China, real-time monitoring data was obtained from the CNEMC (http://www.cnemc.cn).	Wang et al., 2020
	The AQI underwent revisions and the parameter INAQS was used	Mahato et al., 2020
	Air pollutant concentration data were extracted from the ARPA	Collivignarelli et al., 2020
	Atmospheric pollutant data from CETESB	Nakada and Urban, 2020
	Meteorological data and air pollutant concentrations were obtained from the Indian CPCB	Sharma et al., 2020
O_3	NASA used the ozone monitoring instrument on the AURA satellite The dynamics of atmospheric pollutants was studied using satellite data (TROPOMI instrument)	Wang and Su, 2020
	Based on ESA, which used the Copernicus Sentinel-5P satellite to track and observe air pollution in the atmosphere.	Wang and Su, 2020
	The dynamics of atmospheric pollutants was studied by satellite data (TROPOMI instrument)	Venter et al., 2020
	In China, real-time monitoring data was obtained from the CNEMC (http://www.cnemc.cn).	Wang et al., 2020
	The AQI underwent revisions and the parameter INAQS was used	Mahato et al., 2020
	Air pollutant concentration data were extracted from the ARPA	Collivignarelli et al., 2020
	Data on atmospheric pollutants and climatic conditions were obtained through SMAC's automatic monitoring system	Dantas et al., 2020
	Atmospheric pollutant data from CETESB	Nakada and Urban, 2020
	Meteorological data and air pollutant concentrations were obtained from the Indian CPCB	Sharma et al., 2020
	Data on atmospheric pollutants and weather conditions were obtained through SMAC's automatic monitoring system.	Siciliano et al., 2020
	Meteorological data were provided by Meteocat and MITECO. Pollutant data were obtained from XVPCA.	Tobías et al., 2020

AQI: Air Quality Standard; ARPA: Agenzia Regionale Protezione Ambientale (in English: Local Environmental Protection Agency); CETESB: Companhia Ambiental do Estado de São Paulo (in English: Environmental Company of the State of São Paulo); CNEMC: China National Environmental Monitoring Center; CPCB: Central Pollution Control Panel of India; INAQS: Indian National Air Quality Standards; Meteocat: Meteorological Service of Catalonia; MITECO: Spanish Ministry of Ecological Transition; SMAC: Secretaria Municipal do Meio Ambiente (in English: Municipal Environmental Department); XVPCA: Xarxa de Vigilància i Previsió de la Contaminació Atmosfèrica (in English: Atmospheric Pollution Monitoring and Forecasting Network).

Carbon monoxide

The impact of the lockdown measures on air quality was studied in Italy's Metropolitan City of Milan (MeCiMi) during the COVID-19 pandemic. The researchers evaluated the PL period while schools and universities were closed, and movements in a large part of northern Italy were limited only to rigorously essential needs and to reach the workplace (Collivignarelli et al., 2020). Also, the researchers evaluated the period when a TL was declared with more rigorous measures, which forced the closure of almost all production activities and, therefore, a further limitation of movements (DPCM, 2020b). In MeCiMi, the effect of a PL on CO concentration for air quality was not homogeneous, ranging from 32 to 57.6% (Collivignarelli et al., 2020). When comparing the two periods, PL and TL, respectively, only a slight reduction (6.1%) in CO was observed in the air quality in MeCiMi (Collivignarelli et al., 2020). These aspects confirm that CO emission is more characteristic of vehicles, mainly light-duty vehicles (Ventura et al., 2020), since CO emissions are incomplete combustion processes (Ventura et al., 2019). However, other significant factors can be related to these results, such as low household heating usage due to the closure of many workplaces during TL, and less industrial activity, which includes industries that have some relative influence on CO emissions (1.4 – 3.5%) (Collivignarelli et al., 2020).

After the end of the TL, which caused a drastic reduction in the number of cases, the activities were resumed broadly throughout Italy. However, by the end of 2020, the city experienced frightening mass contamination, with a peak on November 20th, 2020, where some 37,000 new cases were detected. Thus, the local government was forced to take stricter measures to contain the advance of the virus. In 2021, oscillations between openings (January/February) and closings (March/April) continued to occur, which implied different carbon monoxide emissions rates. According to IQAir (2021), for example, the amount of CO emitted daily throughout April 2021 in Milan did not exceed the mark of 0.8 $\mu g\ m^{-3}$. Due to the lockdown measures that have been taken in alternate periods, considering the seriousness of the scenario in each region, the area of Lombardy, which is located in MeCiMi, reentered the red stage in March 2021, which is the most concerning in terms of a rise in the number of cases. Standard measures were taken, which did not include the closure of industrial activities, and only commercial establishments and schools closed. So as it is possible to predict, a slight reduction in CO emission was expected. However, not significant because industrial activities continued in operation (Massarotto, 2021).

A more extensive air quality study in China was carried out, monitoring 366 widely distributed urban areas over the country (Wang and Su, 2020).

Table 2 – Impact on air quality worldwide during the COVID-19 pandemic for the main regulated pollutants.

Continent	Country	City/region	CO (%)	SO_2 (%)	NO_2 (%)	O_3 (%)	$PM_{2.5}$ (%)	PM_{10} (%)
European	Italy	Metropolitan City of Milan (MeCiMi)[1]	-32/-80	NE/-27	-42/-58	+68/+135	-37/-44	-32/40
	United Kingdom	London[2]	-	-	-	-	+9/-6	-
	Spain	Madrid[2]	-	-	-	-	+2/-11	-
		Barcelona[3]	-	-	-47/-51	+58	-	-31
America	Brazil	São Paulo[4]	-36/- 65	-	-30/-54	+30	-26/-32	-
		Rio de Janeiro[5,6]	-30/- 49	-34	-17/-54	+13/+67	-	-17
	U.S.	Los Angeles[2]	-	-	-	-	-31/-51	-
		New York[2,9]	-	-	-	-	-25/-36	-
Asia	India	Delhi[7]	-30	-18	-53	NE	-51	-53
		22 cities[8]	-10	NE	-18	+17	-	-
	China	Wuhan[2]	-	-	-	-	-44/-50	-
		366 sites[9]	-20	-19	-54	+51	-	-
Africa	Morocco	Salé[10]	-	-49	-96	-	-	-75
Oceania	Australia	Sydney[2]	-46	-20	-43	NE	-66	-55

[1]Collivignarelli et al. (2020); [2]IQAir (2020); [3]Tobías et al. (2020); [4]Nakada and Urban (2020); [5]Dantas et al. (2020); [6,7]Mahato et al. (2020); [8]Sharma et al. (2020); [9]Wang and Su (2020); [10]Otmani et al. (2020); [9]Zangari et al. (2020); NE: neglitible value.

According to some researchers, these sites could represent the overall air quality in China (Zhao et al., 2019; Kuerban et al., 2020; Wang and Su, 2020). As reported by Wang et al. (2020), the reduced emissions from transportation and secondary industries were the major cause of reduced CO concentrations (20%) for air quality when control measures during the COVID-19 pandemic were implemented. In China, strong restrictive measures were placed until April 2020. For the city of Wuhan, located in the province of Hubei, a decrease of 16.6% in CO emissions was observed compared to the period before the lockdown (Sulaymon et al., 2021). The lockdown in China was different for each province and included the closure of schools and public transportation, in addition to restricting people's transit. Analyzing the air quality situation in 2021 concerning carbon monoxide emissions, the city of Wuhan, which was the pandemic's epicenter, had alarming levels (Figure 1). According to IQAir (2021), the average CO concentration was 1,800 $\mu g\ m^{-3}$ during January 2021, when the city had not fully reestablished itself. However, in April 2021, concentrations reached values between 5,080 - 10,192 $\mu g\ m^{-3}$ of CO, equivalent to an increase of about 9,000 $\mu g\ m^{-3}$ compared to the beginning of the year. Thus, it is concluded that these sudden increases are directly associated with local activities being fully resumed due to the average number of local cases being almost imperceptible.

Sharma et al. (2020) analyzed the variations in air quality and meteorological data obtained from a network of air quality monitoring stations across 22 different cities before and during the COVID-19 pandemic in India. The results found a decrease of approximately 10% in CO during the lockdown period compared to the previous years (2017-2020) in India (Sharma et al., 2020). Another Indian study showed a reduction of 30.35% in Delhi city (Mahato et al., 2020). This value was higher because CO in urban areas was mainly emitted from road traffic, particularly from gasoline burn. In industrial locations, the average CO concentrations decreased by 21.43% (Mahato et al., 2020). These concentrations gradually changed as local restriction measures were relaxed at the end of 2020 and the beginning of 2021. However, as the situation worsened between March and April 2021, reaching 2.24 million cases between April 18th and April 25th, CO emission levels decreased significantly. According to IQAir (n.d.), CO concentrations in April ranged from 584 to 1,665.6 $\mu g\ m^{-3}$.

The Brazilian government chose to adopt PL measures only. More specifically, in São Paulo, social distancing levels ranged from 47 to 59%, with an average of 54% (Nakada and Urban, 2020). It resulted in a CO emission decrease of 36.1 to 64.8% in urban areas. However, downtown had the highest reductions during the lockdown compared to the five-year monthly mean (Nakada and Urban, 2020). According to Andrade et al. (2017), road traffic accounts for approximately 98% of CO emissions in this city. Similar results were observed in Rio de Janeiro, Brazil, where CO emission reduction levels were 30.3 to 48.5%. Dantas et al. (2020) revealed that the sharp CO decrease is associated with emission reductions due to a 50–80% decrease in light-duty vehicle flow. The number of cases in Brazil has also been increasing since the beginning of the pandemic. About 21 million people were infected, including 615,000 deaths approximately. However, only partial lockdowns were implemented and did not include every state. For the city of São Paulo, which experienced a lockdown from March to July 2020, a reduction of 29.95% in CO levels was noticed, but only when the social distancing index was 52.2% (Noda et al., 2021).

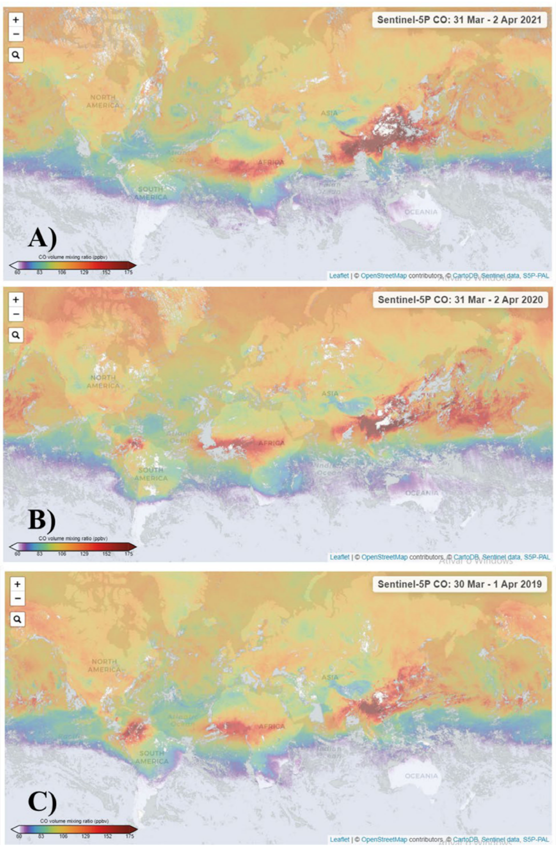

Figure 1 – Map of air quality (CO) around the world: (A) during the COVID-19 pandemic [March to April 2021], (B) during the COVID-19 pandemic [March to April 2020], and (C) before the pandemic [March to April 2019].
Source: Adapted from ESA (2020).

Despite the variations observed in the number of cases between the end of 2020 and the beginning of 2021, the restrictive measures adopted did not interfere as significantly with emissions. According to IQAir, in April 2021, pollutant concentrations ranged from 133.6 to 548.6 μg m^{-3} for the city of São Paulo, which represented an increase of 458 μg m^{-3} compared to the beginning of the same year.

In Sydney, Australia, CO emission reduction was 46%, similar to the other results observed throughout the world. Notwithstanding the variations observed in the number of cases between the end of 2020 and the beginning of 2021, the restrictive measures adopted were very specific and temporary, which did not interfere as significantly with emissions. According to IQAir, in April 2021, pollutant concentrations ranged from 133.6 to 548.6 μg m^{-3} for the city of Sydney, which represented an increase of 458 μg m^{-3} compared to the beginning of the same year.

Sulfur dioxide

In MeCiMi, 70–90% of SO_2 emissions come from power plants, heating systems, and industrial processes. However, the lockdown only led to an appreciable SO_2 drop in Milan city, remaining unchanged in the adjacent areas. In Milan, SO_2 underwent a more marked reduction from the period of PL (19.9%) and a lower decrease from PL to TL (6.8%). It could be partially attributed to a reduction in heating due to the closure of workplaces (*e.g.*, offices), which had a lower influence in the other two adjacent areas (Collivignarelli et al., 2020).

Although in Delhi, India, there was a reduction of 18% in SO_2 levels, they have counted as exceptionally low compared to the other pollutants, not evidencing the prominent definite decrease trend (Mahato et al., 2020). Furthermore, a study across 22 different cities in India showed a negligible change in SO_2 during the lockdown period compared to previous years (2017 – 2020) (Sharma et al., 2020).

In Salé city, Morocco, SO_2 concentrations dropped 49% a few days after implementing the COVID-19 lockdown measures, despite the low SO_2 concentrations recorded in the entire study period (4.75 μg m^{-3} daily) (Otmani et al., 2020).

In China, researchers observed a decrease of 19% in SO_2 concentrations (Wang and Su, 2020). Researchers have generally linked this reduction solely to reduced industrial emissions (Berman and Ebisu, 2020; Wang et al., 2020).

The concentrations of SO_2 worldwide were quite different in places where changes in pollution levels were negligible until significant reductions. Starting at the end of 2020, many cities began to adopt flexible social distancing measures, which implicated certain variations in concentrations of certain pollutants, such as SO2. The city of Milan, for example, began to show a slight increase in the SO_2 percentage after flexibilization. Then, a new lockdown was implemented on March 15th, 2021. From that, it can be imagined that there was a reduction in fuel combustion and, conversely, an increase in the use of heat equipment for the winter (Wang and Li, 2021). Following those proportions, the percentage of SO_2 reduction in 2021 compared to 2020 was not so drastic compared to other atmospheric pollutants.

Similarly, the Indian cities had slight flexibility as of the second semester of 2020 and reentered a period of lockdown on April 19th, 2021. They were considering that most of the SO_2 emissions in India came from power generation plants, a drop of at least 15% on that emission (Rahaman et al., 2021).

China had a tight lockdown for most of the months in 2020, which resulted in a noticeable drop of 62% in SO_2 emissions (Soni et al., 2021). As China was the pandemic's epicenter, the situation at the beginning of the first semester of 2021 was well controlled since the contagion indices were relatively low.

Nitrogen dioxide

NO_2 is an important air pollutant because it has been linked to many health hazards, and its high concentrations can induce the formation of nitrate aerosols and acid rain (Biswas et al., 2019).

In Northern Italy, NO_2 levels showed average reductions of 42% during the PL and 58% during the TL period, which determined a drastic drop in NO_2 concentrations for all areas covered by the study (Collivignarelli et al., 2020). The reductions recorded in MeCiMi are confirmed by the Copernicus satellite system (Figure 2), which highlighted a substantial NO_2 reduction in Milan (47 ± 15%) when compared with the same period in 2019 (ESA, 2020). Furthermore, these results agree with the results (47 to 51.4%) obtained during the lockdown period in other cities in Europe (Tobías et al., 2020). However, with the flexibilization of social distancing in some parts of Europe and activities being resumed in specific civil sectors during the beginning of the first semester of 2021, an intensification in the release of NO_2 gases became notorious. It is estimated, for example, that the city of Milan had an increase of 20-30% in emissions due to increased traffic of local vehicles (Wang and Li, 2021).

According to Collivignarelli et al. (2020), vehicle traffic is the main source of NO_2, which in MeCiMi accounts for 70 ± 3% of the emission of these pollutants, followed by heating systems (15 ± 5%) and industrial processes (11 ± 4%). For this reason, the lower concentrations recorded in MeCiMi could be attributed to the restrictions imposed, when the displacement of humans and loads, and consequently, emissions from vehicles were minimized (Collivignarelli et al., 2020).

Another study in China compared the percent of NO_2 reductions in rural and urban counties. The results showed a drop in concentration of 26 and 16.5%, respectively, with an absolute reduction nearly five times more significant in urban counties. According to the researchers, decreases in NO_2 are likely associated with reduced vehicle traffic from people working remotely and limited domestic travel (Berman and Ebisu, 2020). Additionally, China experienced a reduction of 8.17 μg m^{-3} of NO_2 from late 2019 to mid-April 2020, representing a total of about 20.5% (Zeng and Bao, 2021). However, as measures to control the pandemic remained effective, local openings were identified as early as late August 2020. In February 2021, with the advance of local vaccination, the situation was even better, which resulted in a significant and rapid increase in the emissions of these pollutants, about 35% (Zeng and Bao, 2021).

Although Sharma et al. (2020) have observed a decrease of around 18% in NO_2 during the lockdown period compared to the previous years in India, Mahato et al. (2020) found that NO_2 concentrations dropped in urban areas by as much as 50.6%. In Delhi, India, the results were even higher (52.68%) because this pollutant is mainly emitted from combustion practices and road traffic, particularly diesel-burning and gasoline, manufacturing industry, and power plants. During this lockdown period, all these sectors closed, resulting in a decrease in pollutants like NO_2. However, in industrial sites, NO_2 average concentrations decreased as much as 46% (Mahato et al., 2020). Undoubtedly, pandemic containment measures in India were responsible for improving air quality, especially concerning NO_2 (Sur et al., 2021). A record number in the number of deaths was recorded on April 21st, 2021, which led the local government to implement a new lockdown period, mainly because the vaccination rate in the country is relatively low (1.3% of the population is fully vaccinated). Given these oscillations, it was not possible to accurately say how much NO_2 was detected in the local atmosphere. However, a percentage drop is expected between April, May, and June 2021, due to the crisis in local healthcare. For example, the city of New Delhi, India, whose detection of NO_2 in April 2021 was 52 μg m^{-3}, in February of the same year was about 66 μg m^{-3} according to the Air Quality Index (PlumeLabs, 2021).

Urban areas were also studied in São Paulo, Brazil, where the observed NO_2 concentration reductions ranged from 30.1% to 54.3% during the PL compared to the five-year monthly mean (Nakada and Urban, 2020). Road traffic accounts for approximately 68% of nitrogen oxides (NOx) in the city in usual circumstances (Andrade et al., 2017). These reductions were significant between March 16th, 2020, and July 20th, 2020. The maximum reduction in São Paulo was observed when social distancing measures were adopted in more than half of the region, about 52.20% (Noda et al., 2021). According to IQAir (2020), an average fall of 8 μg m^{-3} of NO_2 is expected in São Paulo. In Rio de Janeiro, NO_2 levels decreased from 16.8 to 53.8% during the PL. This was attributed to local and interstate bus circulation, massive cancellations of flights and cruises, and the reduced demand for energy production (Dantas et al., 2020). At the beginning of 2021, Rio de Janeiro also saw the number of COVID-19 cases and deaths oscillate back and forth, which led to varied restriction measures.

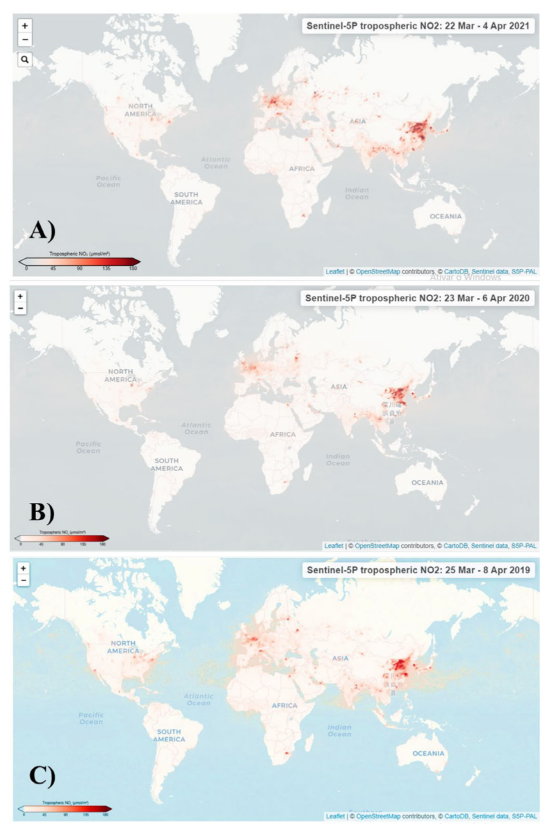

Figure 2 – Map of air quality (NO_2) around the world: (A) during the COVID-19 pandemic [March to April 2021], (B) during the COVID-19 pandemic [March to April 2020], and (C) before the pandemic [March to April 2019].
Source: Adapted from ESA (2020).

In April of the same year, activities were partially resumed, and the NO_2 average concentration for the month was 64 μg m^{-3} (PlumeLabs, 2021).

In Australia, a reduction in NO_2 level concentration by as much as 40% during the lockdown period of Feb/Mar 2020 was observed, compared to the three-year average for February – March (Venter et al., 2020). In Sydney, this value was relatively higher — 43%. In April 2020, Australia continued to show a reduction in NO_2 in several cities, such as Victoria (21%) and NSW (8%), because of social distancing measures (Ryan et al., 2021). However, as of July 1st, 2020, the number of new cases began to increase in the country, mainly because of new variants, reaching its maximum value of 715 cases on August 5th, 2020. From that date on, the country had drastic contaminant falls and, consequently, a return in NO_2 emissions, mainly from vehicle traffic. In 2021, the situation was already well-controlled (new cases ranging between 1 and 24) and normalized, with evidence obtained through the gradual increase in NO_2 emissions, about 11 μg m^{-3} on April 3rd, 2021, and 24 μg m^{-3} on April 28th of the same year, according to AQI.

The most dramatic decrease worldwide was observed in Salé city, Morocco, which reached 96% after 10 days of starting the control measures compared to 10 days before it. According to the researchers of this study, this could be explained by the fact that the emergency measures established by the Moroccan authorities were very strict, including cessation of industrial and transportation activities, which had, as a consequence, a limitation on NOx emission from both industrial production and vehicle exhaust (Otmani et al., 2020). These measures were loosened in the second semester of 2020, which increased the number of cases and reached a peak on November 18th, 2020. Thus, the Moroccan authorities alternated periods of social distancing and flexibility, resulting in variations in pollutant emissions from anthropogenic sources. This confirms how social distancing can alter the composition of the atmospheric air (Venkat Ratnam et al., 2021). In 2021, the situation did not change much in the Morocco region, as cases ranged from 159 to 1,777 until April 21st, 2021. Thus, the region increased emissions between January and March 2021 (29 μg m^{-3}) and a fall was seen in April (15 μg m^{-3}).

Tropospheric ozone

In contrast to other pollutants, the only air pollutant that did not show reductions worldwide was tropospheric O_3 because it is a secondary atmospheric pollutant formed by the interaction of sunlight with NOx and volatile organic compounds (VOCs). Furthermore, the relationship between ozone, VOCs, and NOx is driven by nonlinear photochemistry and is better explained by the VOCs/NOx ratio in the atmosphere (da Silva et al., 2018; Dantas et al., 2020).

Ozone concentrations increased up to 67% during the PL period in Rio de Janeiro city (Dantas et al., 2020; Siciliano et al., 2020). Similar trends were observed in Barcelona (+58%), in China counties (+51%), São Paulo (+30%), and Indian cities (+17%) (Nakada and Urban, 2020; Sharma et al., 2020; Tobías et al., 2020; Wang and Su, 2020). Lung damage, respiratory symptoms, chronic obstructive pulmonary disease, increased morbidity, and mortality are health problems caused by short- and long-term exposures to tropospheric O_3 (Jiang et al., 2016).

The increase in ozone levels has been explained due to a decrease in nitrogen oxides concentrations (NOx = NO_2 + NO) (Andrade et al., 2017; Tobías et al., 2020). At low VOCs/NOx ratios (in general, equal to or lower than 6), the process is controlled by VOCs. In these situations, reducing NOx at constant VOCs leads to increased ozone concentrations. Therefore, the better way to decrease O_3 is by reducing VOC emissions (da Silva et al., 2018; Dantas et al., 2020; Wang et al., 2020).

In Milan city, the increase was more accentuated than in the other three areas studied by Collivignarelli et al. (2020). They attributed higher average benzene concentrations in Milan than the adjacent areas that might have promoted more significant O_3 formation despite the significant decrease in NO_2 (Collivignarelli et al., 2020). Ozone concentration increases have been associated with a decrease in NO, which may cause a decrease in ozone consumption, thus leading to a higher ozone concentration (Andrade et al., 2017; Tobías et al., 2020). According to IQAir (n.d.), ozone concentrations in April 2021 ranged from 39.5 to 96.6 μg m^{-3}, with a monthly average of 44 μg m^{-3}. The higher O_3 levels are usual during spring and summer when higher solar radiation (intensity and duration) occurs, which promotes the photolysis of NO_2. For this reason, more daylight hours (from 9.5 ± 0.2 h before the lockdown period to 12 ± 0.2 h during the TL period) might appear to be a crucial factor causing higher O_3 concentrations in Italy. However, this aspect is not sufficient to explain the fact that the O_3 concentrations during the TL period have been remarkably higher (59 ± 2 μg m^{-3}) than from 2016 to 2018, the average concentration for the same period (35 ± 5 μg m^{-3}) (Collivignarelli et al., 2020). In April 2021, the average ozone emission was 60.6 μg m^{-3}, with a maximum peak of 96.6 μg m^{-3} on April 25th, 2021 (IQAir, 2021).

For the second semester of 2020, the world's ozone levels are better described by the graphic below. There is a tendency to increase ozone concentration considering the period from July to September 2020. However, from October to December, the opposite happened, with a significant decrease in tropospheric ozone concentrations. This sudden variation must be due to the changes in social distancing measures in the countries that compromised the main sources of NO, such as transportation emissions. The last months of 2020 were marked by a significant comeback in industrial and social activities, causing an increase in NO emissions and consequently the decay in tropospheric ozone levels.

Li et al. (2018) and Wang et al. (2020) attributed the increases in O_3 levels during the COVID-19 control measures to decreases in fine particles ($PM_{2.5}$) and lowered fine particles. According to these researchers, $PM_{2.5}$ would be less scavenging of hydroperoxy radicals (HO_2), which would increase peroxy radical-mediated, resulting in greater O_3 production. Other hypotheses shown by some researchers were that the decrease in PM concentrations would increase O_3 levels, resulting in more sunlight passing through the atmosphere. Therefore, it encouraged more photochemical activities and thus higher O_3 production (Li et al., 2018; Dang and Liao, 2019).

$PM_{2.5}$

In 7 out of 10 cities studied, drastic restrictions on people's movement and economic activity imposed during lockdowns resulted in $PM_{2.5}$ reductions of 25-60% (Figure 3) compared to the same period last year (IQAir, 2020). While all cities demonstrated a drop in $PM_{2.5}$ levels during lockdown conditions compared to 2019, cities with higher $PM_{2.5}$ concentration levels, such as Delhi, Mumbai, and Wuhan, showed the most dramatic reductions in $PM_{2.5}$ (IQAir, 2020).

The IQAir report on the impact on air quality, especially for $PM_{2.5}$, during the COVID-19 pandemic in the largest cities around the world (in Europe, Asia, and America) showed a reduction in the average concentrations of 9 to 60% when compared to the same period in 2019. The most considerable reductions were seen in Delhi, India (60%), followed by Wuhan, China (44%), while London and Madrid, both European cities, showed less-intense reductions, 9 and 11%, respectively (IQAir, 2020). Furthermore, when the average concentrations observed during the pandemic were compared to the average of the last 4 years for the same period, the reductions in $PM_{2.5}$ levels ranged from 26 to 55%. However, this comparison revealed that in two European cities (London and Madrid), the $PM_{2.5}$ concentrations (2 - 6%) increased instead of having reduced, which was not expected. Some sources of $PM_{2.5}$, including agriculture and energy production, were not interrupted by the restrictions. This is also evident in countries like Thailand and Australia, which showed an increase in $PM_{2.5}$ levels (Venter et al., 2020). This increase is attributed to the recent forest fires and aerosol levels that have overcome the effect of reduced economic and transportation activities (Reid et al., 2019; Venter et al., 2020).

For the Asian capitals, Delhi, which has a weekly average of 140 μg m^{-3} in normal conditions, showed a 40% $PM_{2.5}$ level reduction during a week of lockdown. Capitals with an average concentration of 121.91 μg m^{-3} (Kabul, Ullabantar, and Kuwait) show an average reduction of 33% in the lockdown period. Capital cities with an average concentration of 106.83 μg m^{-3} (Kabul, Colombo, and Tashkent) show a reduction of 28%. Tehran has a typical weekly concentration of 90 μg m^{-3}. However, its reduction during the lockdown week was 39%. Astana, which has an average weekly concentration of 61.25 μg m^{-3}, reduced its $PM_{2.5}$ concentration by 18% during the lockdown period (Rodríguez-Urrego and Rodríguez-Urrego, 2020). Delhi's $PM_{2.5}$ levels remained stable throughout India's lockdown period and up to July 2020 (Roy and Singha, 2021; Sahoo et al., 2021).

Regarding China, the Copernicus Atmosphere Monitoring Service was used to analyze $PM_{2.5}$ data and observed a reduction of approximately 20-30% in February 2020 (month average) compared to the monthly average for the same period in the previous three years, namely 2017, 2018, and 2019 (Zambrano-Monserrate et al., 2020). This reduction in $PM_{2.5}$ was attributed to lower secondary industry activities (Wang et al., 2020).

An analysis of $PM_{2.5}$ levels was carried out in New York, Los Angeles, Zaragoza, Rome, Dubai, Delhi, Mumbai, Beijing, and Shanghai. The authors considered December 2019 to March 2020 and compared it with the previous years, from 2017 to 2019. The average concentration of $PM_{2.5}$ in New York was 9.48 μg m^{-3} from December 2019 to March 2020. In March 2020, compared to March 2019, the reduction in $PM_{2.5}$ levels was 32%, and in February 2020, compared to February 2019, the reduction was 20%. In Los Angeles, a reduction of 4% in $PM_{2.5}$ is observed during March 2020 compared to March 2019, and this reduction reaches about 30% comparing February 2020 with February 2019. Such changes are associated with the lockdown and rainfall, clearly showing an improvement in air quality (Chauhan and Singh, 2020), but, as it will be shown later, the forest fire season in the United States greatly affected $PM_{2.5}$ levels in Los Angeles. In Indian cities, Delhi and Mumbai had a 35 and 14% decline, respectively, in March 2020 compared to March 2019 (Chauhan and Singh, 2020). However, according to Kumari and Toshniwal (2020), the difference in $PM_{2.5}$ levels was 20.8% for Mumbai and 20.2% for Delhi when comparing both years. Furthermore, air quality in polluted cities like Beijing, Wuhan, Delhi, and Mumbai improved significantly from January to June 2020 due to the lockdown restrictions (Kumari and Toshniwal, 2020).

Different regions were analyzed in India during the lockdown, compared to the same period in the last four years, to assess the effects of the measures taken on air quality. In this specific study, the authors observed a 43% reduction in $PM_{2.5}$ (Sharma et al., 2020).

Regarding $PM_{2.5}$, the concentration reduction from the restriction period to the PL phase (37.1 - 44.4%) is evident in Milan. Compared to an average concentration in the restriction period of around 40 μg m^{-3}, both Milan and the hinterland $PM_{2.5}$ concentrations were almost halved in the TL phase (47.1 - 47.4%). The low reduction from the PL to the TL period can also have been caused by the relatively low contribution of the industrial sector to $PM_{2.5}$ emissions in Milan (15.3 and 25.9%, respectively) (Collivignarelli et al., 2020). $PM_{2.5}$ levels were also analyzed in 17 European capitals, where in typical weeks, they recorded concentrations of $PM_{2.5}$ below 80 μg m^{-3}, and in 50% of the European capitals studied, during the lockdown, they tended to have decreased levels of $PM_{2.5}$, on average 23% (Rodríguez-Urrego and Rodríguez-Urrego, 2020). The reduction in $PM_{2.5}$ in a PL and TL can also be attributed to the simultaneous reduction in the concentration of other pollutants, such as volatile organic compounds, which act as precursors in the formation of secondary $PM_{2.5}$ (Chen et al., 2017; Han et al., 2018).

In the USA, observed $PM_{2.5}$ reductions were more significant in the states that instituted the early closure of non-essential businesses. Reductions in $PM_{2.5}$ were also observed in urban counties with 0.31 μg m^{-3}, while rural counties did not show a significant reduction when comparing data on the lockdown period and previous data (Berman and Ebisu, 2020). Another study shows that, in New York, a reduction in $PM_{2.5}$ levels (36%) was observed right after the lockdown. However, using a linear time interval model, no difference was found when the values were compared with measurements made during the same period in 2015 – 2019 (Zangari et al., 2020).

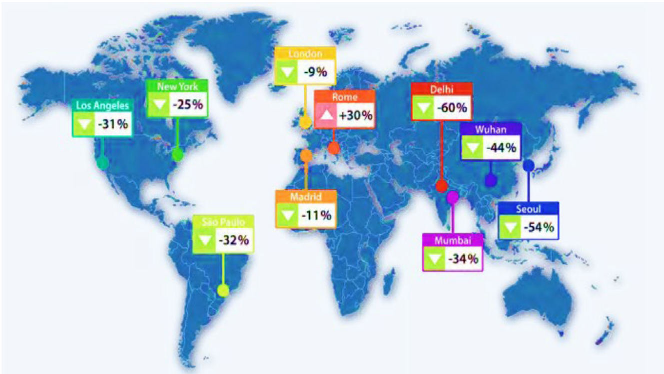

Figure 3 – Map of reduction (%) in $PM_{2.5}$ levels when comparing the 2020 lockdown period to the same period in 2019.

Source: adapted from: https://www.IQAir.com/earth?nav. Accessed Dec, 2021.

Another study carried out in Brazil in the city of São Paulo shows a reduction of 29.8% in $PM_{2.5}$ during the partial lockdown period, comparing the average of the same period with the previous 4 years (Nakada and Urban, 2020).

Following the COVID-19 report, IQAir released the 2020 World Air Quality Report, focusing on $PM_{2.5}$ as the most dangerous type of particulate matter, especially given the current conditions. This report highlighted several other cities, and a deeper analysis was provided (Figure 4) (IQAir, 2021).

It is not hard to understand that some cities with $PM_{2.5}$ are apparently on the rise, such as Sao Paulo (+5%), Melbourne (+1%), and Los Angeles (+1%) after corrections, but that is due to forest fires on their respective countries, which expel a great amount of particulate matter to nearby cities (IQAir, 2021). The difference between the $PM_{2.5}$ and NO_2 variation rates could also be due to the many countries eliminating lockdown restrictions towards the end of the year. This can be visualized by using IQAir's AirVisual database, which keeps track of over 10,000 cities around the world, and is briefly reported in Table 2.

The main characteristic that should be noted in Table 3 above is the higher levels in the first two or three months before lockdown periods began and in the last month or two, depending on the city. To cite a few examples, Delhi, Kabul, Mumbai, Milan, Wuhan, and Rome are the cities where this is most apparent. As Roy and Singha (2021) predicted, particulate matter levels are quickly rising back to normality in many cities as lockdown restrictions are lifted after the end of the first wave of the SARS-CoV-2 virus. Nonetheless, with the rise of the second and even the third waves, some countries are being forced back into a quarantine state. Currently, the general variation in air pollution is tied to the severity of the pandemic worldwide due to the nature of the lockdown measures.

PM_{10}

The PM_{10} changes registered in the Lombardy region in February exceeded the values required in Europe, which are similar to those recommended by the WHO (50 μg m^{-3}), with values reaching 87 μg m^{-3}, in some cases exceeding this standard for up to 13 days in the period from February 10th to March 27th (Bontempi, 2020). This last piece of data was selected considering that in the city of Milan, the average PM_{10} ranged from 47.1 to 56.8 μg m^{-3} before the pandemic. After the partial lockdown, this average decreased from 32.7 to 40.5%. It was probably attributed to the significant reduction in vehicle traffic due to transfer restrictions imposed by the authorities, considering that transport represents the primary source of PM_{10} in Milan (Collivignarelli et al., 2020). The TL period marked an additional general reduction in PM_{10} of 13.1 - 18.9% compared to the PL. This result can be partly attributed to a halt in industrial activities that allowed for reduced direct emissions and, consequently, reduced workers transfers (Collivignarelli et al., 2020). Further analysis of PM_{10} levels took place in Puglia, a southeastern suburban region, from January to August 2020 compared to an average for the same period, from 2016 to 2019. Although the authors observed a reduction when analyzing the data (14%), they concluded it was not statistically significant, concluding that lockdown measures did not affect air quality in this area (Donateo et al., 2021).

In Barcelona, Spain, the Copernicus Tropospheric Monitoring Instrument was used, and the local organization provided data from air pollution monitoring traffic stations to assess changes in air quality during the lockdown. The authors observed a 31% reduction in PM_{10} (Tobías et al., 2020) 350 km away, in Valencia. PM_{10} level reductions were measured up to 47% even during post-lockdown periods, stretching up to October 2020 (Donzelli et al., 2021). India showed similar results as Barcelona, where the authors observed a reduction of 31% in the PM_{10} during lockdown compared to the same period of the last four years (Sharma et al., 2020).

To assess the air quality situation in Delhi, India, during the lockdown period, data from thirty-four air quality monitoring stations covering different regions of the megacity were taken into account, mean PM_{10} concentrations were reduced by about -51.84% (Mahato et al., 2020). As previously mentioned, this could have been due to economic difficulties (Roy and Singha, 2021). The main source of PM_{10} in Delhi is road traffic (around 30% of the annual average), followed by industrial activity, construction works, and dust resuspension as the other sources (Mahato et al., 2020). With the city lockdown, it is expected that the decrease in traffic contributed to the decrease in PM_{10} levels.

Continuous measurements of PM_{10} were performed before and during the lockdown in the city of Salé in Morocco. A decrease in PM_{10} concentrations from 114.6 μg m^{-3} before the lockdown to 28.3 μg m^{-3} during the lockdown was recorded, which corresponds to a decrease of 75% (Otmani et al., 2020).

In the last weeks of March, a partial lockdown was implemented in Brazil in the city of Rio de Janeiro. Thus, there was a clear decrease in PM_{10} compared to the first two weeks of March, of 21.4% in Irajá, 17.5% in Bangu, and 33.3% in Tijuca (Dantas et al., 2020).

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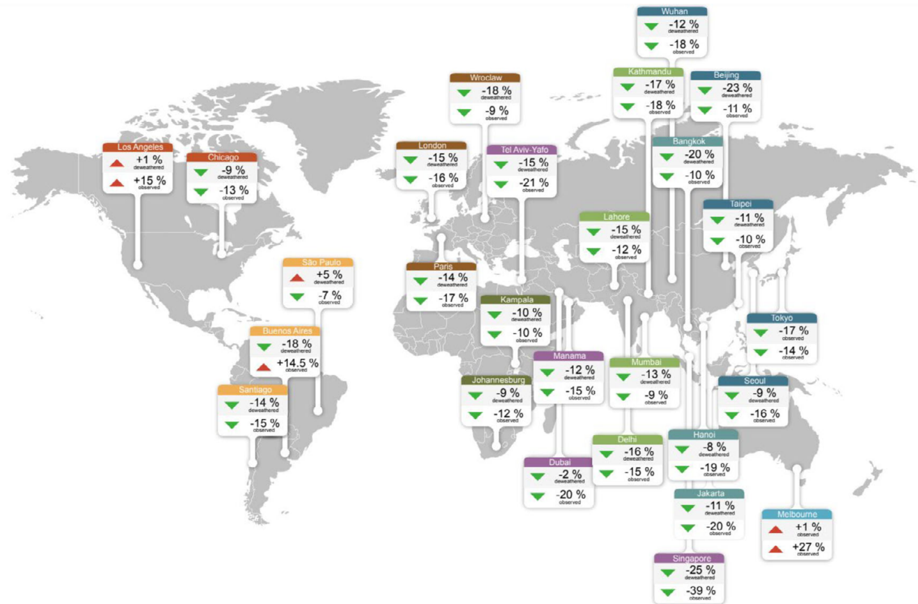

Figure 4 – Map of observed and de-weathered change (%) in $PM_{2.5}$ levels when comparing the 2020 yearly average to 2019.
Source: adapted from https://www.iqair.com/world-most-polluted-cities/world-air-quality-report-2020-en.pdf. Accessed Dec, 2021.

Table 3 – $PM_{2.5}$ monthly and annual concentrations (μg m^{-3}) for different cities worldwide.

City	Average monthly $PM_{2.5}$ concentrations in 2020												
	AVG 2020	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
Delhi, India	84.1	128.1	99.8	54.8	53.6	55.2	52.5	42	35.5	58.9	128	143.6	157.3
Kabul, Afghanistan	46.5	93.6	64.3	35.8	20.9	13.6	20.4	19.8	26.3	27.6	40.8	104.5	117.1
Mumbai, India	41.3	68.8	73.3	46.2	31.6	20.6	15.9	18.6	20	24.7	42.1	63.8	70.6
Wuhan, China	36.5	58.6	37.1	32.5	32.8	33.9	18.8	20.6	19.8	29	34.9	38.7	78.6
Shanghai, China	31.5	53.1	32.4	26.3	33	37.9	28.8	27.2	19.9	24.9	19.7	26.7	47.1
Tashkent, Uzbekistan	29.9	38.2	31.2	35.6	21.2	22.1	22.3	24.6	28.9	32	36	35.5	43.4
Tehran, Iran	29	30.5	24.5	19.7	16.3	21.4	26.2	27.5	26.8	32.2	38.7	34.8	49.1
Milan, Italy	28.4	61.8	36.8	25.9	24.1	10.8	10.4	11.1	9.9	14.6	26.8	49.7	40
Colombo, Sri Lanka	22.4	37.8	40.4	34.8	19.2	15.3	15.9	14	9.8	9.4	16.4	23.7	28.6
Rome, Italy	13.6	32.3	17.1	12.9	12.5	7.9	6.8	9	10.2	10.6	8.5	18	17.2
Madrid, Spain	9	13.9	14.6	6.9	5.9	6.8	7.5	10.5	8.2	7.4	6.9	12.1	7.1
Zaragoza, Spain	7.3	10.4	9.7	6.4	4.9	5.9	5.4	7.5	6.6	7.6	7.3	10.4	7.1

Source: adapted from https://www.iqair.com/world-most-polluted-cities. Accessed Dec, 2021.

Research on PM_{10} levels was also done in Bogotá and Medellín, Colombia, during the COVID-19 lockdown. On average, changes in PM_{10} included a 44% decrease during the total lockdown and 58% during the partial lockdown. The decline was slow during the total lockdown period, as it took almost 10 days for the levels to start decreasing and reaching a low level; also, the biomass burning events in March and April may have contributed to this less pronounced decrease during the total lockdown period (Mendez-Espinosa et al., 2020). Going further, general PM_{10} emissions around the country have been shown to drop about 17% when comparing January - June 2020 with the same period in 2018, which can be mostly associated with the lockdown restrictions that lowered vehicle traffic and, consequently, fuel consumption (Bolaño-Ortiz et al., 2020).

The PM_{10} pattern, derived mainly from road traffic, exhaust from industrial activities, and dust from construction works, can presumably be a reflection of the rapid decrease in traffic density (Sharma et al., 2020).

Conclusion

Pieces of evidence worldwide firmly pointed out that COVID-19 government policies that limited the movement of people resulted in a statistically significant reduction in the levels of air criteria pollutants (CO, NO_2, SO_2, PM_{10}, and $PM_{2.5}$), mainly in urban areas due to decreased vehicle traffic. In almost all cities assessed on five continents, the air quality guidelines recommended by World Health Organization (2021) for human health protection were achieved during PL and/or TL periods, except for tropospheric ozone, which has been increasing (7 - 67%) with the reduction of NOx emissions. The increase in the concentrations of the pollutants studied immediately after the end of the lockdown period is a strong indication that additional control strategies must be implemented so that air quality continues to improve.

Although lockdown globally has contributed to a positive impact on air quality, it is essential to highlight the high negative impacts on social and economic aspects. On the other hand, during the COVID-19 pandemic, there is an alternative path to reduce air anthropogenic pollutant emissions and achieve air quality improvements when significant restrictions on emissions sources are implemented by adopting efficient mitigation strategies and better plans to control air pollution.

Contribution of the authors:

DE FALCO, A.: Project administration, Writing — Review & Editing; VENTURA, L.M.B.: Data curation; Formal Analysis; Methodology; Writing — Original Draft; SANTA-HELENA, E.: Writing — Review & Editing; MEZIAT, G.C.: Formal Analysis; SILVA, L.C.S.: Formal Analysis; PEDREIRA, M.F.S.: Formal Analysis. GIODA, A.: Supervision.

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