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Article

COVID-19 Lockdown Impact on Air Pollution: A Global Comparative Analysis

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Abstract: The goal of this study is to develop a global analysis, based on data from 2015 to 2022, that clarifies the impact of containment policies (e.g., lockdown and quarantine) for Coronavirus Disease-2019 (COVID-19) on the air pollution between countries of different continents. In this context, average changes of CO, NO_2, SO_2, O_3, $PM_{2.5}$, and PM_{10} concentrations based on measurements at ground level in January, February, and March for 2019, 2020, 2021, and 2022 are compared with average values of 2015-2018 period between 300 cities of 19 countries in 5 continents. Results show that the maximum reduction in pollutant concentrations during this period is given by: CO (-4,367.5%) in France, NO_2 (-150.5%) in China and Australia, SO_2 (-154.1%) in Israel, O_3 (-94.1%) in China, $PM_{2.5}$ (-41.4%) in Germany and PM_{10} (-157.4%) in Turkey. Findings reveal that the effects of containment policies on air quality vary significantly between countries depending on different geographical characteristics of regions. This study has main environmental policy implications because it clarifies the critical role of severe control measure to reduce air pollution and support sustainable environment and development.

Keywords: COVID-19 lockdown; Restriction policies; Air pollution; Environmental science; Sustainability.

1. Introduction

Coronavirus Disease-2019 (COVID-19) pandemic crisis, started in 2019 with the novel viral agent SARS-CoV-2, has caused and is generating main socioeconomic problems worldwide with high numbers of deaths and infected people, affecting societal behavior, institutions, economic system and also environment (Coccia, 2020, 2022; Skirienė et al., 2021). The transmission dynamics of COVID-19 is driven by manifold factors, such as high density of cities, high level of air pollution, intensive commercial trade, atmospheric stability, etc. (Bontempi et al., 2021; Bontempi and Coccia, 2021; Coccia, 2020a, Coccia, 2021, 2021a, 2021b; Núñez-Delgado et al., 2021). To minimize the effects of the SARS-CoV-2 virus, which turned into an issue covering worldwide, nations have implemented non-pharmaceutical measures, such as partial or full lockdown measures on a regional or national scale, especially during the peaks of the COVID-19 outbreaks (Coccia, 2021a, 2021c, 2022a, 2022b). In the initial phase of COVID-19 pandemic, the SARS-CoV-2 virus was spreading rapidly between crowded human groups, and lockdown restrictions were the best option to stop or slow down the transmission of the novel virus from human to human (Coccia, 2021c). Restriction policies based on full lockdown and quarantine activities have generated a negatively impact on countries' economies but they have also reduced air pollution nationally and regionally (Anil and Alagha, 2021; Coccia, 2021c; Islam et al., 2021; Le et al., 2020; Munir et al., 2021; Mor et al., 2021). After China, the first countries to apply a partial lockdown are Italy and Iran because numbers of confirmed cases

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and deaths increased rapidly (Coccia, 2021a, 2021c). In the year 2020, partial or full lockdown were carried out in many nations worldwide (Coccia, 2021c; Srivastava, 2021).

By estimating the decrease in especially traffic density in the areas imposed in the lockdown measures, it is expected that air quality in such an environment would be improved. Manifold studies show different results. Li et al. (2020) determine the effects of COVID-19 lockdown on air quality in the Yangtze River Delta region of Eastern China. Results suggest in 2020 significant reductions in the concentrations of air pollutants from industry and traffic emissions because of the diminishing of human activities. The reduction in pollutant concentrations in 2020, which contributed considerably to the improvement of the region's air quality, were found for fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), when were compared data to the year of 2019 (Li et al., 2020).

Sannino et al. (2021) analyze the influence of the lockdown measures on the air quality in the city of Naples, Italy, from March 13 to May 4, 2020, analyzing gaseous pollutants (benzene (C_6H_6), carbon monoxide (CO), NO_2 and SO_2) and particulate matter (PM_{10}, $PM_{2.5}$, PM_1) at ground level comparing these pollutant concentration values to observed data during the same period of the previous year. Results showed that NO_2 was reduced by 49–62% in urban and green suburban areas, while CO and SO_2 showed a higher reduction in urban or industrial districts of the city (50–58% and 70%, respectively). The particulate matter at ground level also showed a reduction ranging between 29 and 49% (Sannino et al., 2021). Another study by Benchrif et al. (2021) investigated how air pollution levels ($PM_{2.5}$ and tropospheric NO_2) change before, during, and after lockdown in 21 cities around the world. Results showed a reduction in NO_2 concentrations ranging from 3 to 58% during the lockdown period, except for three cities (Abidjan, Conakry, and Chengdu), which observed an increase in the NO_2 levels at a rate of 1, 3 and 10%, respectively. Instead, $PM_{2.5}$ levels exhibited an increase after the lockdown period.

Bray et al. (2021) analyzed the variations in air pollutants (CO, NO_2, SO_2, O_3, $PM_{2.5}$, and PM_{10}) comparing the lockdown period (March and April 2020) to same months in 2015 and 2019, using data from both satellite observations for NO_2 and ground-based measurements for remaining pollutants. Globally, NO_2 observations were reduced by approximately 9.19% and 9.57% in March and April 2020. On a regional scale, most monitoring sites in Europe, the USA, China, and India showed declines in the concentration of air pollutants containing CO, NO_2, SO_2, $PM_{2.5}$, and PM_{10} during the lockdown period, whereas only O_3 concentrations increased during the same period. In Valencia (Spain), Donzelli et al. (2021) assessed the impacts of lockdown measures on air quality and pollutant emissions, including nitrogen oxides (NO_x), nitric oxide (NO), NO_2, PM_{10}, $PM_{2.5}$, and O_3, comparing the period of restrictions in 2020 and the same period in 2019. They highest reduction of the PM_{10} and $PM_{2.5}$ levels for the València Centre, València Avd Francia, and València Pista de Silla is given by 58%–42%, 56%–53%, and 60%–41% respectively. Similarly, a significant reduction in nitric oxide levels was also recorded in all air monitoring stations. In particular, NO_x, NO_2, and NO concentrations decreased in the range of 37.4%–65.5%, 35.7%–67.7%, and 35.3%-63.5%, respectively, in 2020. Finally, O_3 levels decreased during the lockdown period. Filonchyk et al. (2021) analyzed the variations of air quality parameters ($PM_{2.5}$, PM_{10}, NO_2, and SO_2) in Poland, comparing data of the lockdown in 2020 with the same data in 2018 and 2019 for five large cities. They showed reductions of aerosol concentrations in the air column in April and May 2020 of approximately -23% and -18% compared to 2018–2019. For $PM_{2.5}$ and PM_{10}, the reductions were from -11.1% to -26.4% and -8.6% to -33.9% in April 2020 and from -8.7 to - 21.1% and -8.5% to -31.5% in May 2020 as compared to the same months in 2019.

Instead, Lonati and Riva (2021) investigated the changes in the concentration of gaseous air pollutants containing NO_2, benzene, and ammonia-based during lockdown restrictions applied in the Po Valley of Northern Italy, comparing data with those of the previous six years, on monthly, daily and hourly bases. Results indicated that air quality showed improvements during the 2020 spring because of the reductions in the nitrogen

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oxides and benzene emissions , close to -50%, for the decrease in road traffic at in urban areas. However, ammonia concentration almost stayed constant, even at high-volume traffic sites. Clemente et al. (2022) analyzed in urban regions of the western Mediterranean, the influence of COVID-19 control measures on concentrations of PM_1, $PM_{10,}$ and their chemical components (water-soluble ions, organic and elemental carbon, and major and trace metals) by comparing data during the lockdown in 2020 to the same period over the previous five years. Results revealed that average decrease in NO_x and traffic-related volatile organic compounds were higher than 50 %, while O_3 concentrations did not exhibit significant variations during the study period. Moreover, a 35 % decrease in PM_1 and PM_{10} levels was observed when Saharan dust events were excluded from the period under study. Hence, traffic restrictions during the lockdown contributed to important reductions in concentrations of elemental carbon and metals derived from road dust. In addition, nitrate showed the largest reductions due to the drop in local emissions of NO_x regarding secondary inorganic aerosols.

Cucciniello et al. (2022) analyzed the impact of lockdown measures in Avellino city of Italy on air pollution by analyzing the concentrations of CO, O_3, $PM_{2.5}$, PM_{10}, C_6H_6, and NO_2 during the period January–December 2020. They showed significant reductions in CO, $C_6H_{6,}$ and NO_2 pollutants during the lockdown period between March 9 and May 18, 2020. In a study implemented in Kabul (Afghanistan), Himat (2021) analyzed the city's air quality by examining air pollutants containing PM_{10}, $PM_{2.5}$, CO, SO_2 NO_2, and O_3 for pre- and post-COVID-19 period. Emission data for different regions of Kabul between 2020 and 2018 showed exceeded the standard values of 150 and 75 μg/m^3 for 24 hours, especially for $PM_{2.5}$ and PM_{10} ten times. The same situation has been observed in SO_2 concentrations; the increase is due to high utilization of stone slag in different regions of Kabul, especially in high-rise buildings and bathrooms. Moreover, air pollution decreased in Kabul for the period of February-April 2020 with control measures for COVID-19, whereas the average concentration of $PM_{2.5}$ emissions increased in May 2020 when lockdown restrictions were suspended.

Other studies to determine the changes in the air quality based on the COVID-19 lockdown restrictions in different countries have been performed by Kutralam-Muniasamy et al. (2021) for Mexico city, Mor et al. (2021) for Chandigarh, located in the Indo-Gangetic plain of India, ,Chowdhuri et al. (2022) for Kolkata Metropolitan Area (India), Das et al. (2022) for Mumbai (India), Pal et al. (2022) focused on Indian cities of Delhi, Mumbai, Kolkata, and Chennai, Sathe et al. (2021) also analyzed some Indian cities (e.g., Mumbai, Bengaluru, and Kolkata), Wetchayont et al. (2021) for Bangkok Metropolitan (Thailand), Jakob et al. (2022) investigated the changes in the concentration of air pollutants of Jakarta (Indonesia), Upadhyay et al. (2022) analyzed changes in levels of air quality in South Asia, Gao et al. (2022) for Wuhan (China), Celik and Gul (2022) investigated the case study of Istanbul (Turkey), Anil and Alagha (2021) and Alharbi et al. (2022) studied the Kingdom of Saudi Arabia, Sbai et al. (2021) the city of Lyon and the center of the Auvergne-Rhône-Alpes region (France), Jeong et al. (2022) conducted a similar study for Toronto (Canada), Gorrochategui et al. (2022) analyzed the Barcelona metropolitan area and other parts of Catalonia, Skirienė et al. (2021) examined the United Kingdom, Spain, France, and Sweden, as well as the Northern Italy region, etc.

Table 1 systematizes studies that analyze the effects of the control measures to cope with the spread of the SARS-CoV-2 virus per main parameter of air pollution in different periods across countries.

In general, these studies show significant reductions of the concentrations of primary air pollutants CO, NO_2, SO_2, $PM_{2.5,}$ and PM_{10}, one of the secondary pollutants O_3 but also the concentration of CO_2 (Gillingham et al., 2020; Liu et al. 2020; Kumar et al., 2022).

Most of the studies just mentioned investigated the effects of the lockdown measures on air pollution until 2021. In order to expand these studies, the goal of this paper is to also analyze the relationship between lockdown and effect on air pollution until August 2022, using new data. In particular, this study here analyzes changes in CO, NO_2, SO_2, O_3,

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$PM_{2.5,}$ and PM_{10} air pollutant concentrations of nineteen countries from five continents from 2015 to 2022. Next section presents the methods of inquiry for this purpose.

Table 1 Studies concerning the associations between COVID-19 lockdown measures and air quality parameters

Parameter	**Region, Country**	**Variation in air pollutants**
CO	Bogota, Colombia	23-34% reduction (Amaya and Samuel, 2022)
	Quito, Ecuador	48.75% reduction (Phuong Ngoc et al., 2022)
	Beijing-Tianjin-Hebei, China	20.40% reduction (Wang et al., 2021)
	Dhaka, Bangladesh	8.8% reduction (Rahman et al., 2021)
	Delhi, India	30.35% reduction (Mahato et al., 2020)
	Nagpur, India	63% reduction (Navinya et al., 2020)
	USA and China	19.28 – 25.53% reduction in USA and China (Shakoor et al., 2020)
	Santiago, Chile	13% reduction (V et al., 2021)
NO_2	Bogota, Colombia	13-22% reduction (Amaya and Samuel, 2022)
	Delhi and Mumbai, India	60-78% reduction for Delhi and Mumbai (Kumari and Toshniwal,
	Barcelona, Spain	2022)
	Quito, Ecuador	66% reduction (García-Dalmau et al., 2022)
	China	63.98% reduction (Phuong Ngoc et al., 2022)
	Vietnam	19.1 ± 9.4% reduction (Wu et al., 2022)
	Nagpur, India	24-32 % reduction (Dang and Trinh, 2022)
	Makkah, Saudi Arabia	69.2% reduction (Saini et al., 2022)
	Beijing-Tianjin-Hebei, China	58.66% reduction (Habeebullah et al., 2022)
	Dhaka, Bangladesh	37.80% reduction (Wang et al., 2021)
	Bangladesh	20.4% reduction (Rahman et al., 2021)
	United Kingdom	40% reduction (Islam et al., 2021)
	Leeds, Sheffield, and Manchester,	38.3% reduction (Jephcote et al., 2021)
	England	37.13–55.54% reduction (Munir et al., 2021)
	Ankleshwar, Vapi and Gujarat, India	80.18% reduction (Nigam et al., 2021)
	Delhi, India	52.68% reduction (Mahato et al., 2020)
	Bengaluru (Bangalore), India	87% reduction (Navinya et al., 2020)
	USA and China	36.7 – 38.98% reduction in USA and China (Shakoor et al., 2020)
	Rio de Janeiro and São Paulo, Brazil	10-40% reduction (Siciliano et al., 2020)
SO_2	Bogota, Colombia	11-20% reduction (Amaya and Samuel, 2022)
	Delhi and Mumbai, India	19-39% reduction for Delhi and Mumbai (Kumari and Toshniwal,
	Quito, Ecuador	2022)
	Nagpur, India	45.76% reduction (Phuong Ngoc et al., 2022)
	Dhaka, Bangladesh	64.3% reduction (Saini et al., 2022)
	Bangladesh	17.5% reduction (Rahman et al., 2021)
	USA and China	43% reduction (Islam et al., 2021)
		3.81% increase in the USA – 18.36% reduction in China (Shakoor et al., 2020)

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Table 1 continued, Studies concerning the associations between COVID-19 lockdown measures and air quality parameters

Parameter	Region, Country	Variation in air pollutants
O_3	Bogota, Colombia	31.3-14.1% increase (Amaya and Samuel, 2022)
	Barcelona, Spain	27% increase (García-Dalmau et al., 2022)
	Quito, Ecuador	26.54% increase (Phuong Ngoc et al., 2022)
	Makkah, Saudi Arabia	68.67% increase (Habeebullah et al., 2022)
	Morocco	22-28% increase (Sbai et al., 2022)
	Dhaka, Bangladesh	9.7% reduction (Rahman et al., 2021)
	Bangladesh	7% increase (Islam et al., 2021)
	United Kingdom	7.6% increase (Jephcote et al., 2021)
	Santiago, Chile	63% increase (Toro et al., 2021)
$PM_{2.5}$	Bogota, Colombia	7-15% reduction (Amaya and Samuel, 2022)
	Quito, Ecuador	42.17% reduction (Phuong Ngoc et al., 2022)
	Jiangsu, China	18% reduction from pre-COVID; 2% decrease in post-COVID (Bhatti
	Valencia, Spain	et al., 2022)
	Toronto, Canada	3.1% increase (Ródenas et al., 2022)
	Beijing-Tianjin-Hebei, China	4% reduction (Jeong et al., 2022)
	Leeds, Sheffield, and Manchester,	21.50% reduction (Wang et al., 2021)
	England	29.93–40.26% reduction (Munir et al., 2021)
	New Delhi, Chennai, Kolkata,	62% reduction in, followed by Mumbai (49%), Chennai (34%), and
	Mumbai, and Hyderabad, India	New Delhi 26% (Ravindra et al., 2021)
	Ahmedabad, India	68% reduction (Navinya et al., 2020)
	Santiago, Chile	11% reduction (Toro et al., 2021)
PM_{10}	Bogota, Colombia	25-16% reduction (Amaya and Samuel, 2022)
	Delhi and Mumbai, India	55-44% reduction for Delhi and Mumbai (Kumari and Toshniwal,
	Jiangsu, China	2022)
	Barcelona, Spain	19% reduction from pre-COVID; 23% increase in post-COVID (Bhatti
	Valencia, Spain	et al., 2022)
	Makkah, Saudi Arabia	37% reduction (García-Dalmau et al., 2022)
	Beijing-Tianjin-Hebei, China	16.5% reduction (Ródenas et al., 2022)
	Leeds, Sheffield, and Manchester,	12% reduction (Habeebullah et al., 2022)
	England	33.60% reduction (Wang et al., 2021)
	Delhi, India	2.36–19.02% reduction (Munir et al., 2021)
		71% reduction (Navinya et al., 2020)

2. Materials and methods

2.1. Research setting and sample

This study was focused on a global scale, considering the main five continents: Asia, Europe, North America, South America, and Oceania except for Africa because there was not constantly available parameters for the examined periods. To investigate air pollution changes at the national scale, we selected 19 countries and 300 cities around the world, having enough and constant data of air pollutants for the statistical analysis in pre-and post-lockdown period. The selected countries were: China, India, Israel, Japan, and South Korea from the Asia continent, Croatia, Denmark, France, Germany, Macedonia, the

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Netherlands, Poland, Serbia, Spain, Turkey, and the United Kingdom from the European continent, Canada and the United States from North America continent, Australia from Oceania continent and Brazil, Chile and Colombia from South America continent.

2.2. Measures and sources of data

To analyze the effects of lockdown during the COVID-19 pandemic on air pollution, six major air pollutants are investigated: CO, NO_2, SO_2, O_3, $PM_{2.5}$, and PM_{10}. Measure of air pollutants is concentration of μg/m^3 (micrograms -one-millionth of a gram- per cubic meter of air). Daily data and measures on six major air pollutants were obtained from the World Air Quality Index Portal from 2015 to 2022 (WAQI, 2022).

2.3. Data analysis procedure

The average monthly concentrations of air pollutants from January to March are compared from 2019 to 2022 with the same months of the 4-year baseline (2015-2018) to account for the effects of containment policies during COVID-19 on air pollution.

The monthly relative rate of change (ROC) was used to compare variance in air pollutants exposure in different periods. ROC is given by (Eq. 1):

$$ROC_m = \frac{[x_{2019m} - x_{(2015-2018)m}]}{x_{2019m}} \times 100 \quad (1)$$

where

ROC_m = the monthly relative rate of change of pollutant concentration in month *m*

x_{2019m} = the pollutant concentration in month *m* in 2019

$x_{(2015-2018)m}$ = the baseline pollutant concentration in month *m* from 2015 to 2018 (He et al., 2021).

ROC values were calculated for January, February, and March months from 2019 to 2022 by staying the baseline period between the years 2015 and 2018. If ROC_m was positive, the pollutant concentrations in 2019, 2020, 2021, and 2022 were higher than baseline (2015–2018), and conversely, if ROC_m was negative, the pollutant concentration in the examined years representing the full or partial lockdown periods of the countries was lower than baseline (He et al., 2021).

3. Results and Discussion

3.1. Results and discussion per countries among continents

The variation % in the concentration of air pollutants based on ROC during the lockdown periods compared with the baseline period (2015-2018) for 19 countries is presented in Table SM-1 (SM= SUPPLEMENTARY MATERIAL). All discussions here are based on ROC instead of mean concentration values of air pollutants presented in Figures 1-5.

Table SM-1 Variation % in the concentration of air pollutants during the lockdown periods compared with baseline period (2015-2018) for 19 countries.

	Variation, % compared with baseline period (2015-2018)					
China	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-116.22	-190.60	-47.90	-70.52	-2.23	12.90
Jan-20	0.29	-96.21	-121.23	-41.88	56.45	57.48
Jan-21	-61.30	-163.43	-50.21	-86.40	30.87	43.55
Jan-22	-80.61	-222.56	-119.40	-76.86	13.59	15.18
Feb-19	-114.74	-186.52	-96.81	-118.87	-18.35	-4.05
Feb-20	-37.57	-117.20	-166.31	-79.38	30.58	23.89
Feb-21	28.23	-164.04	-171.00	-112.20	24.70	16.47
Feb-22	-54.01	-147.09	-122.00	-75.76	23.93	18.00
Mar-19	-137.30	-187.46	-85.64	-120.89	-18.38	5.99
Mar-20	59.79	-105.48	-6.44	-94.08	18.16	20.91
Mar-21	-49.61	-125.53	-83.67	-96.35	33.02	30.76
Mar-22	-33.10	-139.14	-108.38	-73.96	12.84	9.55

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Average value	-49.68	-153.77	-98.25	-87.26	17.10	20.89
Variation, % compared with baseline period (2015-2018)						
South Korea	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-22.1	-15.2	-50.1	4.9	21.5	9.3
Jan-20	-36.2	-37.1	-88.1	3.5	10.8	-22.1
Jan-21	-34.4	-34.7	-102.6	4.1	5.6	-14.4
Jan-22	-51.7	-34.9	-113.1	8.6	10.9	-21.7
Feb-19	-10.3	-2.3	-14.0	10.0	4.7	-4.7
Feb-20	-11.0	-12.2	-43.1	3.3	-7.9	-29.3
Feb-21	-8.8	-10.2	-55.7	11.8	-6.8	-22.4
Feb-22	-44.0	-18.4	-73.4	11.6	-15.9	-32.7
Mar-19	-15.4	-7.1	-15.1	8.2	2.3	0.6
Mar-20	-27.4	-27.4	-54.7	-3.7	-16.2	-22.7
Mar-21	-20.1	-19.5	-72.2	6.2	-6.3	23.9
Mar-22	-39.4	-26.0	-94.1	2.6	-18.0	-18.4
Average value	-26.7	-20.4	-64.7	5.9	-1.3	-12.9
Variation, % compared with baseline period (2015-2018)						
India	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-111.4	-30.5	-64.5	-13.2	21.5	19.3
Jan-20	-109.5	-53.3	-2.7	-19.3	12.5	0.2
Jan-21	-122.4	-24.7	-9.7	-23.9	21.9	25.8
Jan-22	-147.3	-86.4	-1.0	-34.0	15.1	16.5
Feb-19	-131.5	-41.3	-88.2	-40.9	-4.0	-0.1
Feb-20	-114.5	-24.1	16.9	-17.0	-3.6	7.7
Feb-21	-88.2	-7.3	-6.8	-36.9	14.1	35.0
Feb-22	-128.9	-54.0	6.3	-17.6	9.4	23.1
Mar-19	-94.9	-34.5	-74.0	-33.6	9.4	-12.9
Mar-20	-84.0	-69.4	-4.9	-32.0	2.7	-18.0
Mar-21	-75.0	-1.3	9.3	-23.8	27.8	31.3
Mar-22	-62.7	-44.2	13.3	-1.9	21.5	29.5
Average value	-105.9	-39.3	-17.2	-24.5	12.4	13.1
Variation, % compared with baseline period (2015-2018)						
Israel	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-190.6	16.4	-43.5	22.9	17.7	20.1
Jan-20	92.8	53.2	87.4	80.8	62.9	59.0
Jan-21	-165.5	-6.2	-67.6	3.3	9.3	-18.2
Jan-22	-58.8	25.7	29.0	55.8	-11.6	-81.2
Feb-19	-171.8	-3.9	-56.0	-3.6	-21.2	-38.2
Feb-20	83.8	6.7	63.3	38.1	-1.9	32.2
Feb-21	-225.8	5.3	25.5	57.3	-24.2	-95.4
Feb-22	-167.4	27.0	22.6	59.0	-31.2	-59.7
Mar-19	-211.6	-0.6	-90.2	-8.4	-8.2	-26.1
Mar-20	-180.4	-12.3	-154.1	-8.0	-17.6	-15.8
Mar-21	-126.2	10.3	17.9	52.8	-26.7	11.7
Mar-22	-143.5	25.8	0.0	50.1	-45.6	-14.6
Average value	-122.1	12.3	-13.8	33.3	-8.2	-18.8
Variation, % compared with baseline period (2015-2018)						
Japan	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-18.5	-7.0	-10.7	3.5	-6.7	-15.3
Jan-20	-25.5	-18.0	-45.2	-2.7	-14.6	-23.5
Jan-21	-32.2	-12.6	-49.4	-2.7	-9.3	-17.0
Jan-22	-49.4	-14.4	-56.2	1.3	-21.3	-36.0
Feb-19	-7.7	-8.7	-14.5	1.5	1.6	3.1
Feb-20	-15.2	-11.9	-27.9	-6.1	-9.7	2.6
Feb-21	-23.9	-12.2	-34.0	3.5	-8.9	-16.0
Feb-22	-35.1	-22.2	-50.3	0.3	-20.2	-38.1
Mar-19	-19.2	-12.4	-9.7	0.6	-3.3	-5.6

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Mar-20	-29.6	-22.7	-50.0	-12.6	-24.1	-17.9
Mar-21	-32.2	-18.6	-54.4	-5.7	-14.3	-13.6
Mar-22	-5.4	-18.9	-47.2	-3.2	-16.1	-16.3
Average value	-24.5	-15.0	-37.5	-1.8	-12.3	-16.1
Variation, % compared with baseline period (2015-2018)						
Turkey	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-3.4	10.1	-21.0	-3.2	-19.9	-32.1
Jan-20	-30.7	-19.9	6.4	-10.8	-51.5	-143.3
Jan-21	-7.2	-4.1	-10.6	-27.2	-55.5	-153.4
Jan-22	-44.9	-8.3	-1.5	-37.1	-57.3	-137.0
Feb-19	3.2	6.3	-15.8	-10.0	-8.0	-4.2
Feb-20	-41.1	-22.9	2.5	12.2	-47.4	-147.7
Feb-21	-14.8	-10.8	-4.1	-27.2	-43.1	-147.0
Feb-22	-44.5	-10.1	-7.0	-45.2	-32.7	-132.2
Mar-19	4.5	8.4	3.1	-10.0	-9.6	-18.0
Mar-20	-35.8	-21.0	-14.4	-20.1	-44.6	-157.4
Mar-21	-26.9	-19.7	9.9	-33.2	-61.3	-158.5
Mar-22	-89.0	-21.0	0.3	-32.7	-42.9	-149.8
Average value	-27.6	-9.4	-4.4	-20.4	-39.5	-115.0
Variation, % compared with baseline period (2015-2018)						
USA	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-25.6	-5.7	-102.2	1.8	-5.3	3.2
Jan-20	-17.7	-9.5	-147.6	2.2	-13.3	-8.2
Jan-21	-32.9	-16.4	-160.8	4.1	-0.8	36.2
Jan-22	-20.9	-3.4	-104.1	5.9	-2.1	14.3
Feb-19	-31.5	-2.5	-134.3	57.0	3.4	-7.8
Feb-20	-9.2	-10.5	-130.6	4.4	-14.5	-15.6
Feb-21	-24.1	-13.5	-134.3	6.0	-5.5	8.1
Feb-22	-14.1	-5.2	-83.9	6.0	-3.8	6.2
Mar-19	-13.7	13.7	-59.0	56.2	15.5	-8.8
Mar-20	13.8	-23.2	-136.9	-6.8	-15.7	-46.7
Mar-21	-15.7	-8.5	-46.0	4.5	0.2	4.1
Mar-22	-14.1	-6.7	-47.9	3.7	-9.4	-12.4
Average value	-17.1	-7.6	-107.3	12.1	-4.3	-2.3
Variation, % compared with baseline period (2015-2018)						
Canada	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-1010.0	-21.9	-254.6	-25.9	-2.4	41.5
Jan-20	72.6	21.2	51.0	29.5	-7.9	-18.7
Jan-21	-1010.0	-41.3	-265.7	-6.9	-27.2	15.3
Jan-22	-1010.0	-36.9	-194.0	17.3	-110.5	-82.8
Feb-19	-990.0	-6.7	-317.3	-9.8	9.1	26.1
Feb-20	68.9	22.8	54.2	24.9	6.4	-1.4
Feb-21	-990.0	-28.2	-413.2	-5.4	-16.3	1.7
Feb-22	-990.0	-35.0	-278.4	-18.0	-94.3	-67.5
Mar-19	-975.0	1.6	-239.7	-4.7	18.5	34.5
Mar-20	71.1	13.9	48.8	19.4	6.5	19.7
Mar-21	-975.0	-13.1	-268.0	-11.8	2.5	15.0
Mar-22	-128.7	-42.1	-247.0	45.6	-112.3	-81.0
Average value	-655.5	-13.8	-193.7	4.5	-27.3	-8.1
Variation, % compared with baseline period (2015-2018)						
Brazil	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-35.8	18.1	-106.2	25.2	8.5	7.9
Jan-20	-70.4	-16.7	-184.8	-17.3	5.3	-7.3
Jan-21	-79.5	-8.3	-111.8	2.2	0.9	-3.0
Jan-22	-78.8	-3.9	-199.8	-4.6	26.5	-12.3
Feb-19	-15.1	-9.6	-69.4	-6.9	11.1	-26.1
Feb-20	-18.3	-34.1	-46.5	-13.7	-7.2	-21.6

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Feb-21	4.5	-19.6	-19.5	21.1	20.2	-15.9
Feb-22	-50.4	-6.5	-70.5	11.5	23.0	-1.7
Mar-19	-22.2	-20.6	-6.5	11.3	-0.4	-28.4
Mar-20	-112.3	-24.1	5.7	5.9	-6.3	9.2
Mar-21	-57.4	-10.8	-122.9	18.4	22.0	-4.9
Mar-22	-46.7	4.9	-135.3	3.3	-0.4	11.9
Average value	-48.5	-10.9	-89.0	4.7	8.6	-7.7
Variation, % compared with baseline period (2015-2018)						
Colombia	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-150.9	-21.3	39.8	-342.6	-16.5	-37.3
Jan-20	-138.6	26.0	32.2	-108.0	-27.8	-36.8
Jan-21	-93.5	14.1	35.7	-116.3	-26.8	-54.8
Jan-22	-141.8	10.4	93.9	-122.6	-5.7	-61.9
Feb-19	1.7	-16.0	74.2	26.1	31.7	9.1
Feb-20	-9.9	28.6	48.3	58.1	15.2	-36.9
Feb-21	21.5	34.6	69.8	51.0	2.5	-66.4
Feb-22	-24.5	26.8	58.3	53.5	4.0	-78.3
Mar-19	42.5	22.8	63.1	23.7	-6.8	-7.9
Mar-20	-56.1	23.1	-39.0	56.7	-19.8	-46.4
Mar-21	-3.4	46.5	-223.8	35.1	-49.8	-60.9
Mar-22	0.0	32.3	-30.4	33.8	-48.6	-76.7
Average value	-46.1	19.0	18.5	-29.3	-12.4	-46.3
Variation, % compared with baseline period (2015-2018)						
Chile	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	41.1	-8.1	15.7	22.1	-11.6	26.7
Jan-20	13.2	-10.4	-0.7	14.7	-13.7	18.3
Jan-21	22.5	-17.8	16.4	-14.2	25.7	8.9
Jan-22	-10.6	-54.2	-132.1	-13.6	22.5	22.6
Feb-19	18.3	-1.8	6.9	28.3	-1.8	37.4
Feb-20	5.8	-3.7	-9.6	22.1	-11.3	10.4
Feb-21	-32.7	-10.0	-64.7	-10.4	25.9	-13.7
Feb-22	8.3	-19.8	-81.7	5.8	29.8	6.8
Mar-19	-0.8	-3.3	10.2	8.3	-11.9	23.8
Mar-20	2.9	-29.0	16.3	23.5	-21.3	-1.7
Mar-21	-25.6	-22.3	-26.9	-11.7	33.3	24.5
Mar-22	9.6	-8.9	-42.6	5.9	37.6	36.8
Average value	4.3	-15.8	-24.4	6.7	8.6	16.7
Variation, % compared with baseline period (2015-2018)						
Germany	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-110.0	-5.9	-79.3	8.6	-19.5	17.4
Jan-20	-110.0	-0.3	-73.8	-0.7	-4.7	30.6
Jan-21	-110.0	-27.6	-105.7	-1.2	-32.2	-22.5
Jan-22	-110.0	-30.3	-191.1	13.5	-27.3	-17.7
Feb-19	-162.5	19.8	-74.2	6.2	7.5	33.3
Feb-20	-162.5	-10.6	-140.9	21.9	-73.3	-34.3
Feb-21	-162.5	-13.6	-69.6	4.3	-24.7	16.5
Feb-22	-162.5	-25.1	-147.8	25.9	-89.5	-24.9
Mar-19	-132.5	-1.6	-99.3	13.7	-22.5	-11.7
Mar-20	-132.5	-19.4	-26.4	5.8	-41.4	-19.0
Mar-21	-132.5	-13.2	-85.9	4.2	-29.8	-3.6
Mar-22	-132.5	-10.6	-12.3	15.8	2.1	16.4
Average value	-135.0	-11.5	-92.2	9.8	-29.6	-1.6
Variation, % compared with baseline period (2015-2018)						
Netherlands	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	56.8	-9.1	1.7	8.4	9.2	-5.6
Jan-20	10.1	-25.3	-6.7	0.8	3.4	-13.1
Jan-21	5.0	-18.5	-74.4	2.2	-2.5	-37.5

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Jan-22	0.0	-18.0	-46.1	10.7	5.2	-31.8
Feb-19	30.8	5.4	36.5	-7.0	10.4	12.6
Feb-20	3.6	-34.3	-11.2	18.4	-38.8	-9.2
Feb-21	19.6	-11.8	-38.3	9.0	-8.4	3.2
Feb-22	-18.9	-26.0	-32.3	23.1	-23.8	-16.7
Mar-19	-3.2	-21.7	25.1	6.1	-5.5	-5.1
Mar-20	7.7	-25.7	-35.3	6.1	-16.9	-18.2
Mar-21	16.2	-6.8	6.4	8.4	-1.4	11.0
Mar-22	-1.3	-0.5	-20.8	11.6	15.6	18.2
Average value	10.5	-16.0	-16.3	8.2	-4.5	-7.7
Variation, % compared with baseline period (2015-2018)						
Spain	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	30.8	-9.6	-3.8	9.5	0.5	1.7
Jan-20	10.6	-15.7	-2.8	12.5	6.0	1.2
Jan-21	23.3	-37.3	-15.2	3.3	-14.8	-16.1
Jan-22	-360.1	-18.9	-37.8	8.4	2.8	1.0
Feb-19	32.7	16.6	11.9	11.7	23.2	17.5
Feb-20	31.3	-5.8	-1.3	-4.1	20.3	16.0
Feb-21	12.2	-39.1	-30.5	1.9	0.4	9.4
Feb-22	-346.9	-8.7	-7.6	1.3	-0.5	-3.0
Mar-19	17.9	-6.4	-8.2	9.6	4.7	6.3
Mar-20	17.0	-56.6	-46.3	-3.3	4.0	-15.4
Mar-21	9.7	-31.3	-25.6	0.6	-8.0	7.3
Mar-22	-363.7	-53.2	-55.2	-0.6	8.8	40.6
Average value	-73.8	-22.2	-18.5	4.2	3.9	5.5
Variation, % compared with baseline period (2015-2018)						
France	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-261.2	1.7	-31.3	0.1	-6.0	-6.8
Jan-20	-4667.5	-3.2	-46.2	-2.8	-4.7	-8.4
Jan-21	-4667.5	-24.2	-30.7	-6.2	-6.5	-3.6
Jan-22	-4667.5	-24.2	-48.3	-5.3	5.9	-3.4
Feb-19	-81.8	20.3	5.4	7.4	10.9	24.6
Feb-20	-4607.5	-18.8	-47.0	8.6	-43.5	-17.8
Feb-21	-4607.5	-29.4	-50.5	-2.5	-11.1	-0.5
Feb-22	-4607.5	-31.2	-12.3	14.4	-26.8	-15.8
Mar-19	-390.9	-8.6	-7.7	11.1	-29.5	-6.1
Mar-20	-4367.5	-53.4	-61.8	2.4	-23.8	-10.0
Mar-21	-4367.5	-28.0	17.0	0.4	-8.9	13.2
Mar-22	-4367.5	-15.9	-88.8	14.9	7.0	12.5
Average value	-3471.8	-17.9	-33.5	3.6	-11.4	-1.8
Variation, % compared with baseline period (2015-2018)						
United Kingdom	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-9.3	5.2	-22.6	15.4	11.3	29.6
Jan-20	-32.7	-6.5	-7.6	5.4	-15.1	-11.6
Jan-21	-15.6	-28.0	-52.7	-10.7	-9.0	-22.5
Jan-22	-49.8	-18.6	-54.6	3.5	24.1	7.8
Feb-19	29.9	8.1	-16.0	8.5	19.6	41.3
Feb-20	-8.9	-26.8	1.3	11.3	-28.6	-37.1
Feb-21	9.9	-42.4	-79.5	6.6	-14.1	-29.2
Feb-22	-23.4	-56.8	83.6	17.2	-37.9	-48.7
Mar-19	-20.8	-12.8	-47.2	11.0	-11.2	-15.9
Mar-20	-37.7	-25.1	-26.5	7.9	-11.8	-5.3
Mar-21	-3.7	-37.0	-52.9	-0.3	-2.5	-1.3
Mar-22	-70.6	-39.9	-39.8	10.2	16.4	8.4
Average value	-19.4	-23.4	-26.2	7.2	-4.9	-7.0
Variation, % compared with baseline period (2015-2018)						
Croatia	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**

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Jan-19	0.0	-12.7	-51.0	0.8	-70.6	-17.7
Jan-20	0.0	13.6	-146.1	3.3	-8.3	23.1
Jan-21	0.0	-38.0	-168.8	-10.1	-16.1	-19.0
Jan-22	0.0	-14.7	-80.3	-2.6	28.4	5.3
Feb-19	0.0	18.4	30.2	5.6	-18.9	14.5
Feb-20	0.0	1.5	-43.0	17.6	-13.3	-9.0
Feb-21	0.0	5.1	-18.4	-23.3	-2.6	19.2
Feb-22	0.0	-16.3	-32.7	8.4	-1.2	-12.2
Mar-19	0.0	4.1	-84.2	-4.0	-56.7	3.0
Mar-20	0.0	-37.9	-18.6	6.0	-13.8	18.8
Mar-21	0.0	-7.3	-51.3	-9.9	10.3	15.4
Mar-22	0.0	-12.9	-56.5	7.8	20.3	26.5
Average value	0.0	-8.1	-60.1	-0.02	-11.9	5.7
Variation, % compared with baseline period (2015-2018)						
Poland	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-1.0	12.1	-24.6	21.0	34.8	-18.6
Jan-20	-7.7	5.2	-23.5	12.7	35.8	-22.7
Jan-21	1.0	2.0	-22.4	6.5	39.6	50.5
Jan-22	-23.5	-9.1	-56.2	26.3	19.6	-38.1
Feb-19	-8.8	13.1	-4.6	22.4	4.6	-19.0
Feb-20	-36.8	-11.9	-49.9	28.0	-31.4	-72.6
Feb-21	5.3	12.5	14.6	86.6	11.0	1.4
Feb-22	-41.0	-16.3	-52.4	29.8	-47.9	-63.2
Mar-19	-0.3	6.5	-14.6	23.4	-7.7	-17.5
Mar-20	-12.2	-5.6	-23.5	23.1	4.9	-20.4
Mar-21	11.8	7.7	-31.8	18.3	5.6	3.2
Mar-22	-1.5	18.1	-2.7	29.3	14.8	15.6
Average value	-9.6	2.9	-24.3	27.3	7.0	-16.8
Variation, % compared with baseline period (2015-2018)						
Australia	**CO**	**NO_2**	**SO_2**	**O_3**	**$PM_{2.5}$**	**PM_{10}**
Jan-19	-115.9	-190.9	-47.9	-70.5	-2.2	12.9
Jan-20	0.2	-96.2	-121.6	-41.9	56.5	57.5
Jan-21	-61.1	-163.4	-50.2	-86.4	30.9	43.6
Jan-22	-80.9	-222.6	-119.3	-76.9	13.6	15.2
Feb-19	-114.7	-186.3	-96.8	-118.9	-18.4	-4.1
Feb-20	-37.6	-117.0	-166.4	-79.4	30.6	23.8
Feb-21	28.2	-163.8	-171.0	-112.2	24.7	16.4
Feb-22	-54.5	-146.9	-122.0	-75.8	23.9	17.9
Mar-19	-136.4	-187.4	-85.6	-120.9	-18.4	6.0
Mar-20	-61.4	-105.5	-6.5	-94.1	18.2	20.9
Mar-21	-49.7	-125.5	-83.7	-96.3	33.4	30.8
Mar-22	-33.8	-139.1	-108.4	-74.9	12.8	9.6
Average value	-59.8	-153.7	-98.3	-87.3	17.1	20.9

Firstly, variations in air pollutant concentrations of countries from the Asia continent are visualized in Figure 1. When Figure 1 is examined for China, the air pollutant with the highest decrease in concentration values is NO_2 in January 2022 and January 2019 with a rate of 222% and 191%, followed by SO_2 in February 2021 and February 2020 with 171% and 161% (Figure 1-China). The times and rates of the maximum reduction in air pollutants other than NO_2 and SO_2, respectively, are: CO with the rate of 137 %, O_3 with the rate of 120 %, $PM_{2.5}$ with the rate of 18 % in March 2019, and PM_{10} with the lowest rate and only a declining rate as 4 % in February 2019. The full lockdown restrictions implemented in various cities in China starting on 23 January 2020 can be associated with these decreasing trends (Wu et al., 2021). Wu et al. (2021) investigated in China how the COVID-19 lockdown (from 1 January to 12 April 2020) affects traffic-based air pollutants in Shanghai, comparing the pollutant concentrations during the pandemic with the data of 2018-2019 years. They observed a moderate decline in CO emissions with a ratio of 28.8% and 16.4%

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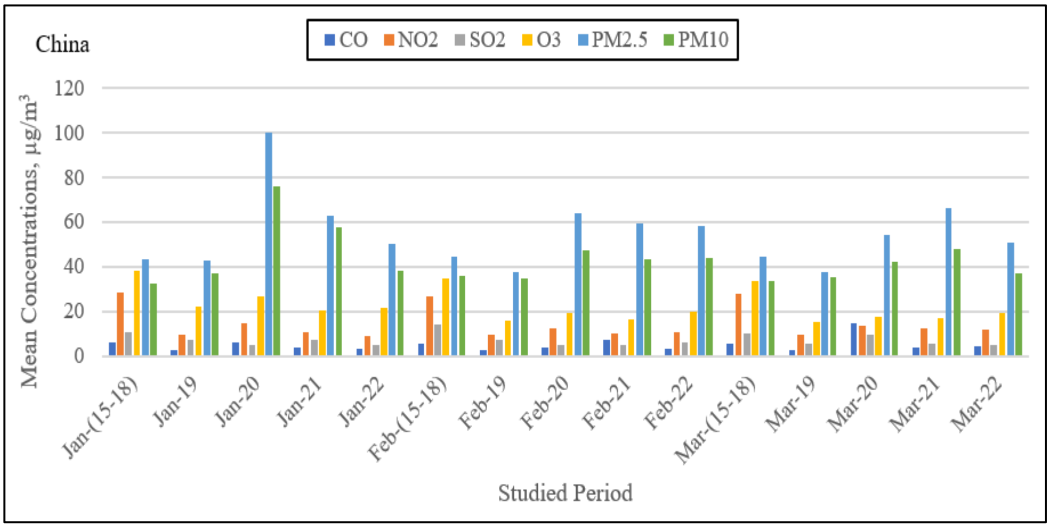
for roadside and non-roadside stations, respectively. In South Korea, the lockdown measures of pandemic control started on 25 March 2020 (Vuong et al., 2020). SO_2 showed the highest decreasing trend in January 2022 (-113%) and January 2021 (-103%) compared with the values of baseline periods 2015-2018. The rate of decrease in the concentrations of air pollutants varied between 2.3% and 113%. While ozone increased compared to the baseline period in all periods except March 2020, $PM_{2.5}$ increased in January 2019, 2020, 2021, and 2022, and in February and March of 2019 (see Figure 1-South Korea). Vuong et al. (2020) explored the effects of the city lockdown on the variation of air pollutant concentrations in Daegu city of South Korea. They observed reductions in the concentrations of air pollutants: ratio of 3.75% (PM_{10}), 30.9 % ($PM_{2.5}$), 36.7% (NO_2), 43.7% (CO), and 21.3% (SO_2). In India, $PM_{2.5}$ concentration values decreased in February of 2019 (-4%) and 2020 (-3.6%), while the remaining periods showed an increasing trend in which the maximum level was observed in March 2021 (28%). Instead, PM_{10} decreased in March of 2019 (-13%) and 2020 (-18%), while there was an increase of 0.2% in January 2022) and 31.3% in March 2021. All air pollutants, except $PM_{2.5}$ and PM_{10}, showed a decrease in the variation for almost all investigated periods, the most effective decrease trend was observed in CO with a rate of 147% in January 2022 when pollutant concentrations are compared with the average values of 2015-2018 baseline period (see Figure 1-India). Reductions in the concentrations of CO (-84%), NO_2 (-69%), SO_2 (-5%), O_3 (-32%), and PM_{10} (-18%) observed in March 2020 in India should be attributed to nationwide lockdown restrictions, which included the banning of all transport activities and closure of industrial, commercial and private establishments, starting from March 2020. In an investigation conducted by Singh and Chauhan (2020), they evaluated the effect of the total lockdown of March 2020 on air quality parameters including $PM_{2.5}$, Air Quality Index (AQI), and tropospheric NO_2 over India by ground and satellite observations. Results pointed out a declining trend in all air quality parameters studied (Figure 1-India).



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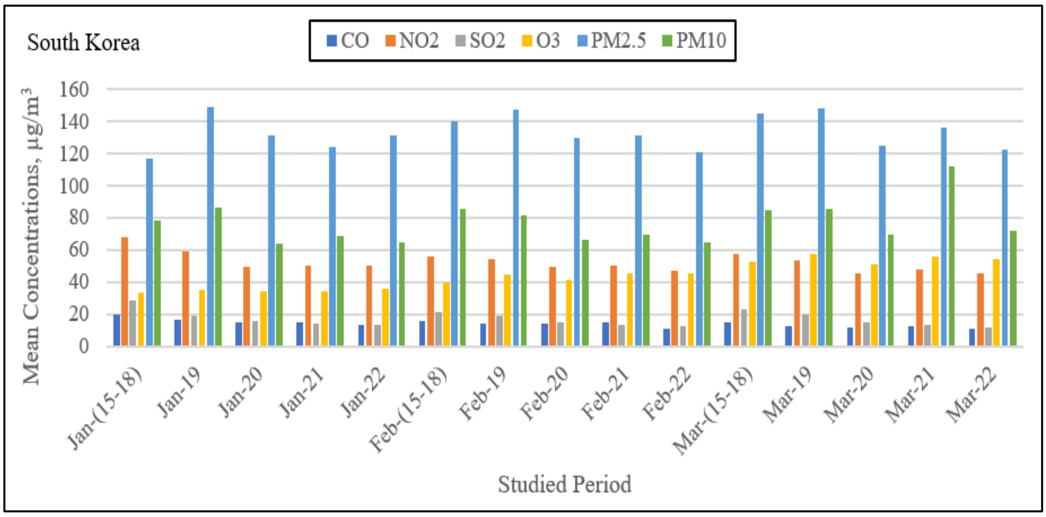

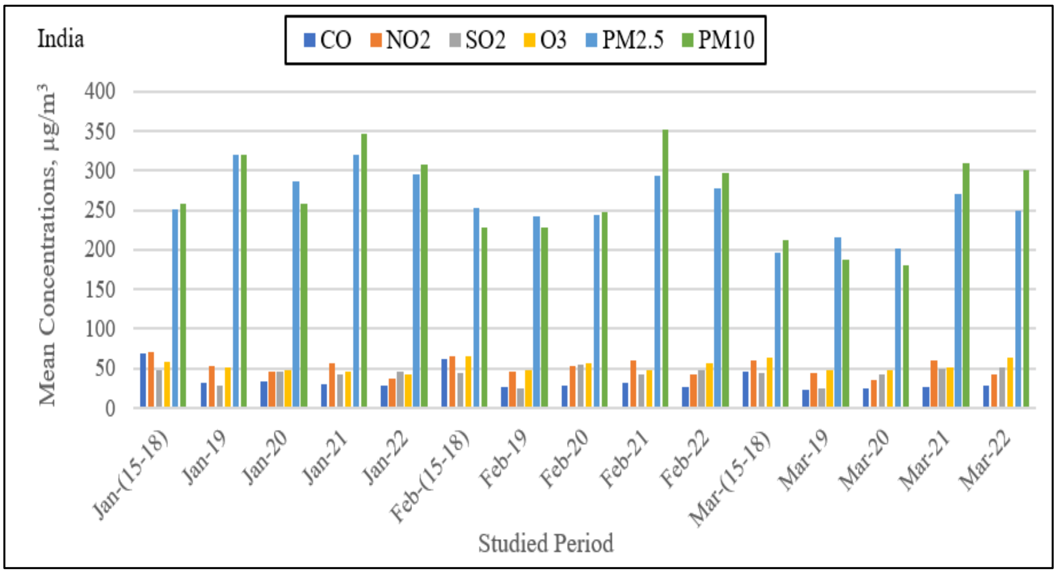

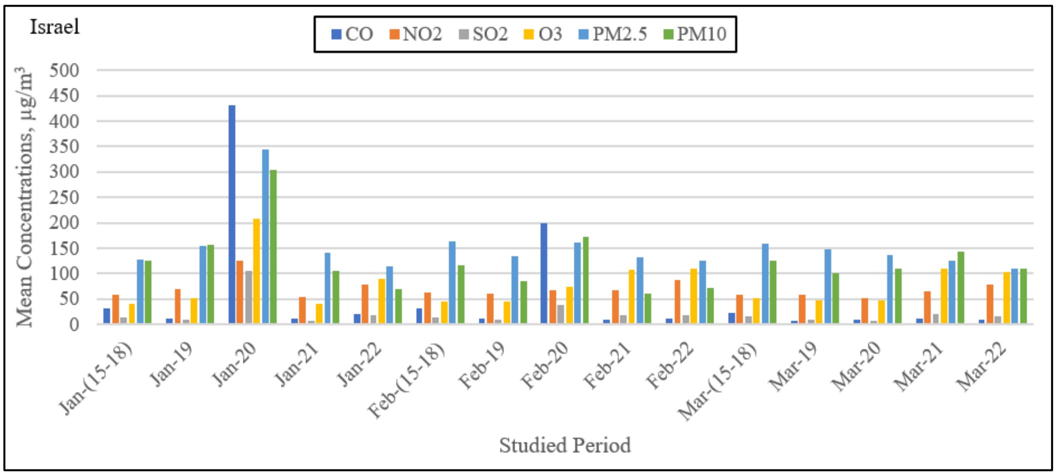

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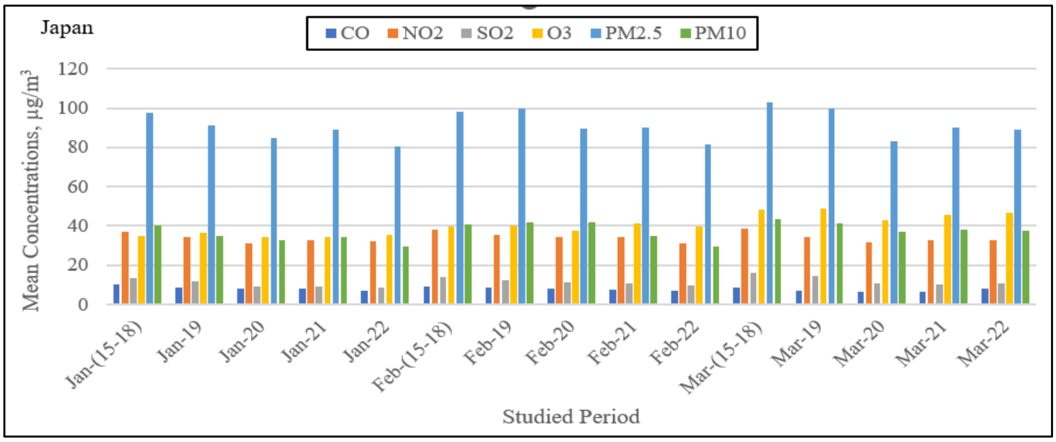

Fig. 1 Mean air pollutant concentrations of examined countries from the Asia continent.

In Israel, a remarkable decreasing trend was observed in CO (-180%) and SO_2 (-154%) in March 2020 which could be attributed to limitations imposed by Israel's government including restrictions on public and private sectors. The highest reduction in the pollutant concentrations for the studied period compared with the control period (2015-2018), known as the pre-COVID-19 period, was obtained in CO in the range of -59% to -226% (see Figure 1-Israel). Agami and Duyan (2021) evaluated the impact of the COVID-19 lockdown on air pollution in Haifa and Greater Tel Aviv, two regions with high air pollution in Israel. They found that pollution emissions reduced during the COVID-19 lockdown relative to the same period in 2019. The biggest reduction was observed in NO_x, which, on average, was 41%.

In Japan, the government declared a state of emergency on 7 April 2020 and 8 January 2021 and implemented a mild lockdown (Yamamato et al., 2022). In January 2021, variations in the concentration of CO and SO_2 showed higher reductions of 34% and 12 % compared to the same month of previous year. Moreover, CO (-49%) and SO_2 (-56%) exhibited a maximum decrease in January 2022, NO_2 (-23%), O_3 (-13%), and $PM_{2.5}$ (-24%) in March 2020, and PM_{10} showed the maximum reduction (-38%) in February 2022 compared with the control period (Figure 1-Japan). Hu et al. (2021) investigated the variation in the levels of air pollution during and after lockdowns in China (Wuhan), Japan (Tokyo), the Republic of Korea (Daegu), and India (Mumbai) comparing *Air Quality Index* (AQI) values for the past three years. Results showed that reduction in air pollutant levels during the examined periods between these cities was positively correlated. In Tokyo, low levels of air pollution were observed during the lockdown.

Changes in air pollutant concentrations based on the pre-and-post-COVID-19 period for the United States of America and Canada from the North American continent are in Figure 2.

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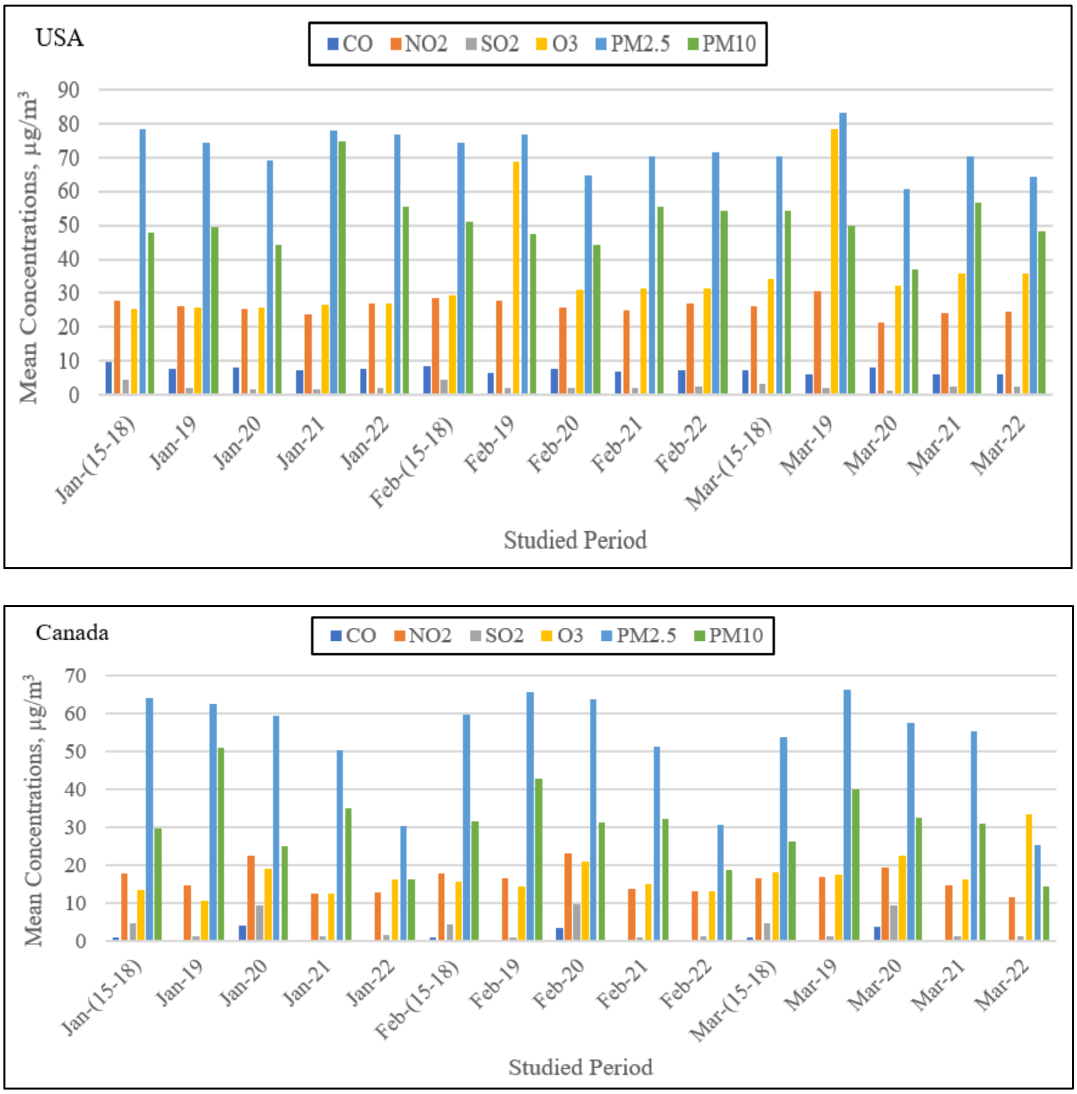

Fig. 2 Mean air pollutant concentrations of examined countries from the North American continent.

In the USA, a national emergency was declared on 13 March 2020 with a shutdown of services and community lockdowns (Khubchandani et al., 2021). In March 2020, the remarkable reductions in the concentration of NO_2 (-23%), SO_2 (-137%), O_3(-7%), $PM_{2.5}$ (-16%) and PM_{10} (-47%) were observed. The highest decreasing ratio was obtained for SO_2 emissions compared with the pre-COVID-19 period (see Figure 2-USA). Shaakoor et al. (2020) investigated the variations in the air pollutants containing CO, NO_2, SO_2, $PM_{2.5}$, and PM_{10} in the USA considering the data during the first quarter of 2019 and 2020 (lockdown period). The results showed that the overall concentrations of CO, NO_2, and $PM_{2.5}$ decreased by 19.3%, 36.7%, and 1.10%, respectively, while PM_{10} and SO_2 increased by 27.8% and 3.81%, respectively in five selected states of the USA during the lockdown period. In Canada, a nationwide lockdown was declared from 22 March to 2 May 2020. Our results are in Figure 2-Canada. Mashayekhi et al., 2021 investigated the impacts of the COVID-19 lockdown measures imposed from 22 March to 2 May 2020 on air quality in Canada's four largest cities (Toronto, Montreal, Vancouver, and Calgary) comparing the values with those in the same periods of the previous decade (2010-2019). Results indicated that NO_2 and $PM_{2.5}$ demonstrated a decreasing trend with respect to the lockdown measures, while O_3 surface concentrations showed an increase up to a maximum of 21%.

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Changes in air pollutant concentrations, based on the pre-and-post-COVID-19 period for countries from the South American and European continents, are in Figures 3 and 4, respectively.

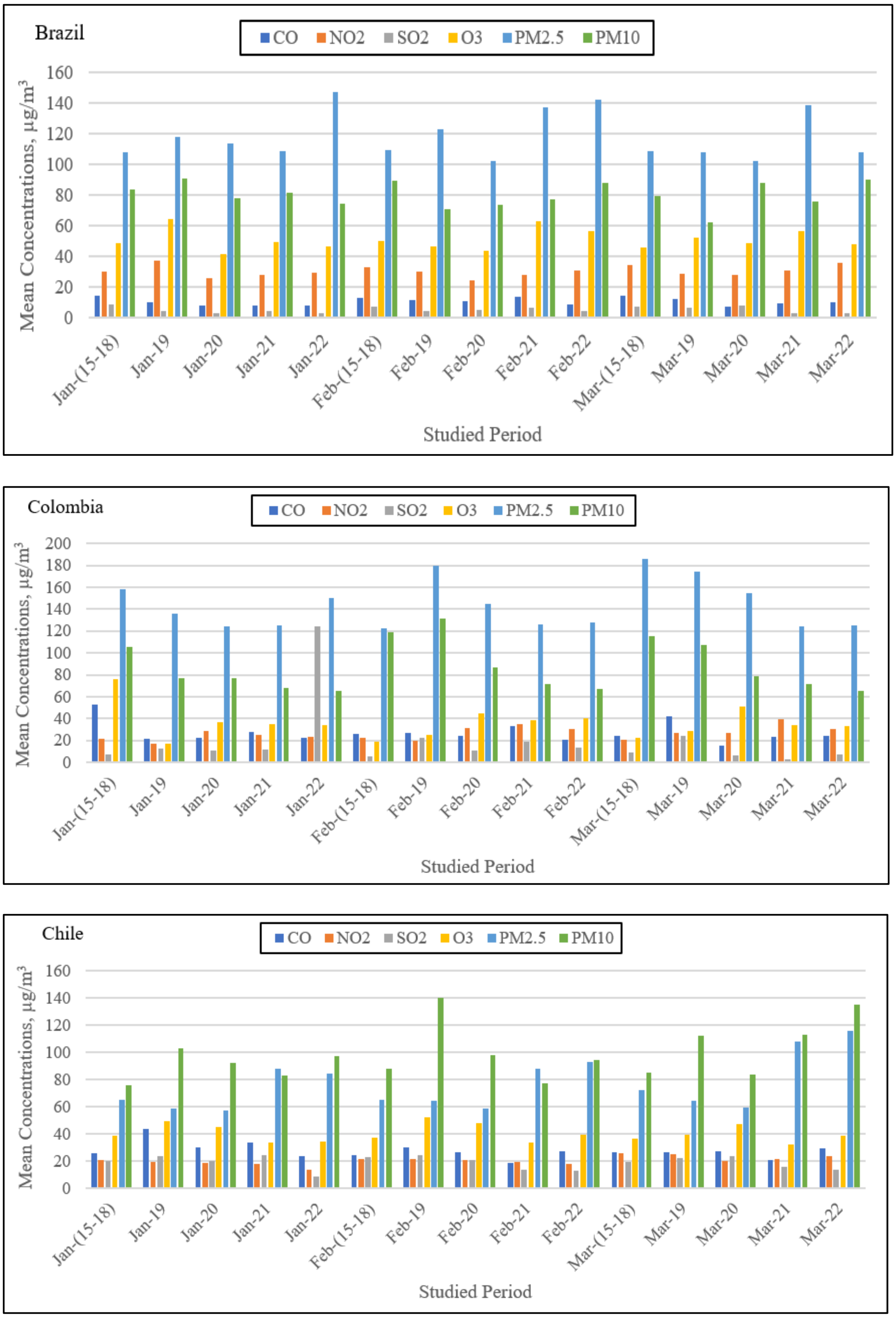

Fig. 3 Mean air pollutant concentrations of examined countries from the South America continent.

In Brazil, a partial lockdown started in March 2020 and ended in June 2020 (Beringui et al., 2022). The effect of lockdown policies on the air quality of Brazil, considering the

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variations in the average air pollutant concentrations in March 2020 relative to the pre-COVID-19 period, shows that the highest decrease ranged from 22 to 112 % was for CO followed by NO_2 (-24%) (see Figure 3-Brazil). Beringui et al., 2022 showed the variation in the air quality during the partial lockdown in Rio de Janeiro city (Brazil). Results showed that CO concentration reduced significantly because of decreasing in the traffic density, while O_3 concentration increased, most probably as a consequence of the reduction in primary air pollutants. Instead, PM_{10} concentration did not exhibit a remarkable variation. In short, the partial lockdown contributed to improving the air quality of Rio de Janeiro city.

In Columbia, the government declared a national lockdown starting from March 20 to August 31, 2020. Variations of pollutant concentrations in March 2020 relative to the pre-COVID-19 period had a reductions in CO (56%), SO_2 (39%), $PM_{2.5}$ (20%), and PM_{10} (46%). Amaya and Samuel (2022) compared the concentration levels of air pollutants in Bogota city (Columbia) during the lockdown and the corresponding levels during the same period in 2018 and 2019. They observed a considerable reduction in traffic flow patterns and a drop in emission levels by -13% and -22% in NO_2, -11% and -20% in SO_2, -23% and -34% in CO, -7% and -15% in $PM_{2.5}$, -25% and -16% in PM_{10}, respectively. On the contrary, levels of atmospheric O_3 increased by 31% and 14% from reference values (Figure 3-Colombia). Finally, in Chile, where lockdown restrictions started in March 2020, the highest variation of concentrations between the pre-COVID-19 period (2015-2018) and post lockdown was observed for SO_2 (-132%) in January 2022, whereas NO_2 (-29%), $PM_{2.5}$ (-21%), and PM_{10} (-2%) showed decreasing trends in March 2020 (see Figure 3-Chile).

As far as Europe is concerned, in Germany, a nationwide lockdown was imposed between March 21 and June 30, 2020 (Balamurugan et al., 2021). The maximum decreases in NO_2 (-30%) and SO_2 (-191%) concentrations were observed in January 2022, whereas the maximum decrease in $PM_{2.5}$ concentration was in February 2022 (Figure 4-Germany). In general, there is a decrease in the concentration of all parameters of air pollution associated with restrictions. Balamurugan et al. (2021) found that anthropogenic emissions in eight German metropolitan areas had reduced mean in-situ NO_2 concentrations by 23% between March 21 and June 30, 2020, whereas the corresponding mean in-situ O_3 concentration increased by 4% between March 21 and May 31, 2020. In the Netherlands (Figure 4-The Netherlands), the lockdown period was from March 16, 2020 to May 10, 2020 (Velders et al., 2021). The mean values of the 2015-2018 baseline are compared with values during the lockdown period and showed a significant decrease in the CO concentration. The concentrations of NO_2 (-26%), SO_2 (-35%), $PM_{2.5}$ (-17%), and PM_{10} (-18%) in March 2020, when the control measures started, were lower than corresponding concentrations in March 2015-2018 in the Netherlands, already before the lockdown period (see Figure 4-The Netherlands). Velders et al. (2021) also investigated the lockdown effects on the concentrations of NO_x, NO_2, PM_{10}, $PM_{2.5}$, and O_3 in the Netherlands, by analyzing observations and simulations with the atmospheric chemistry-transport model, after eliminating the effects of meteorological conditions during the lockdown. They determined, based on statistical analyses, that the lockdown reduced observed NO_2 concentrations with larger values than obtained from simulation models. Reductions in observed $PM_{2.5}$ concentrations of about 20% were also found for all locations, with somewhat larger values than estimates of 5–16% of simulation model.

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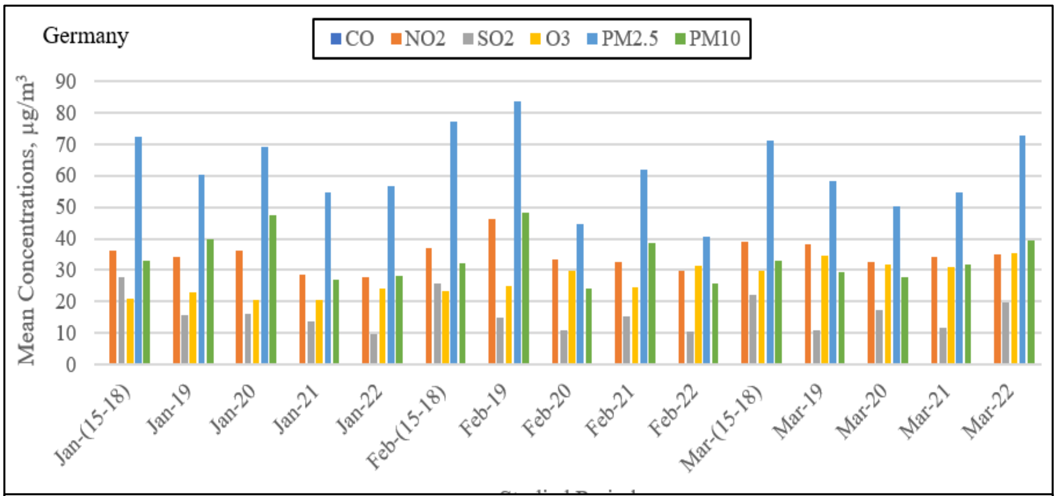

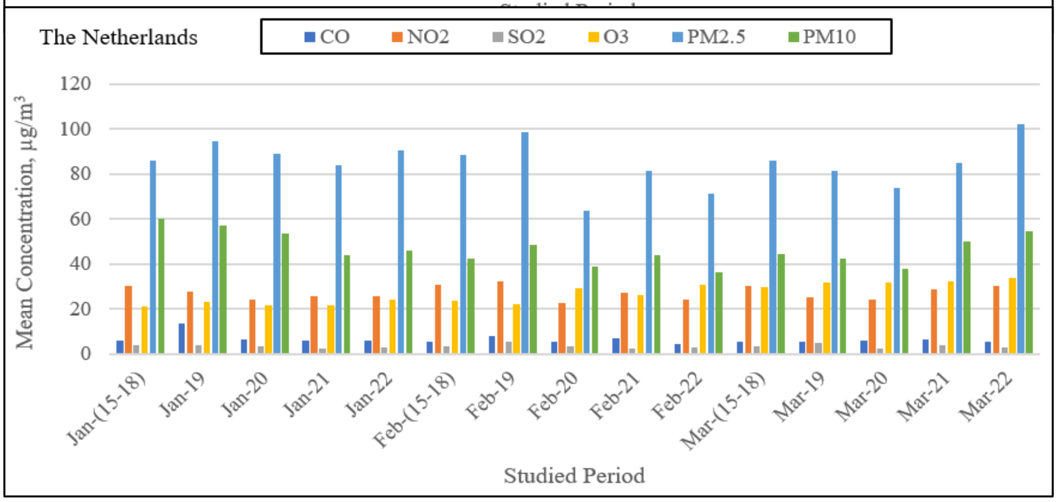

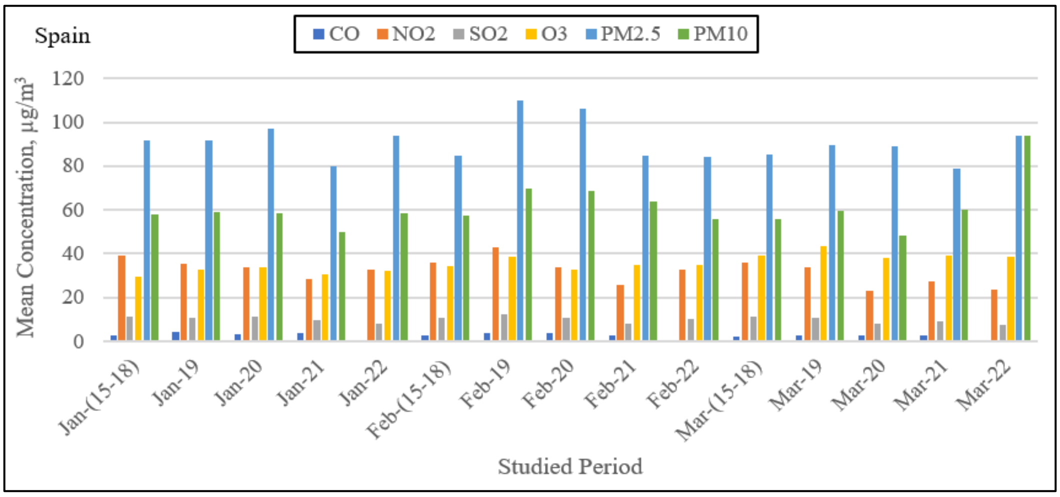

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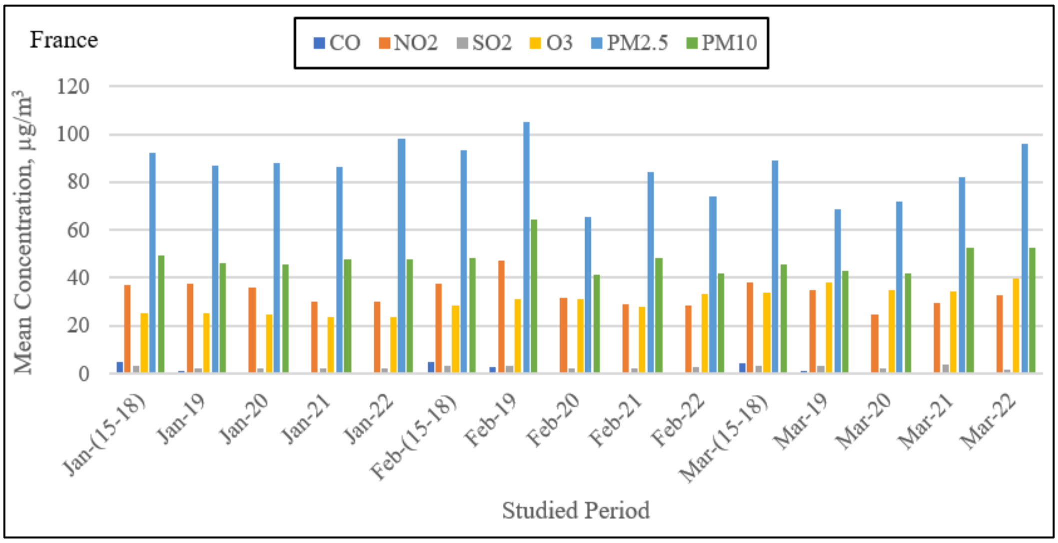

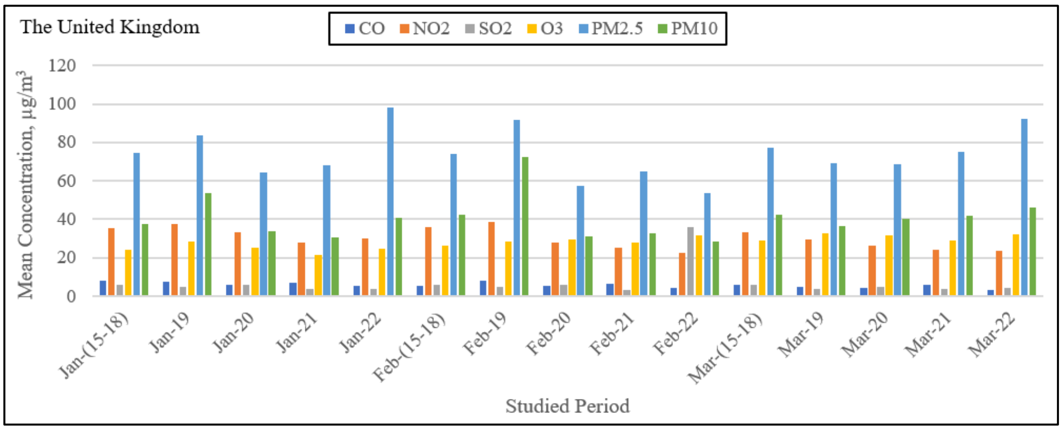

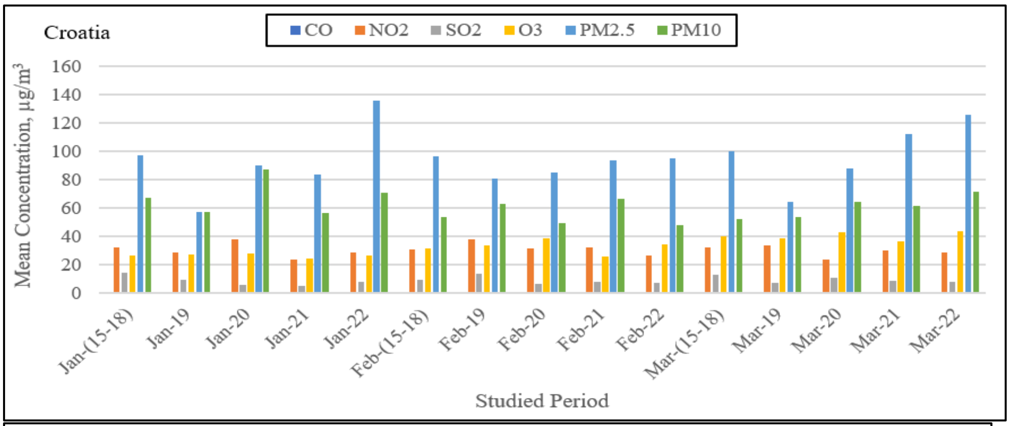

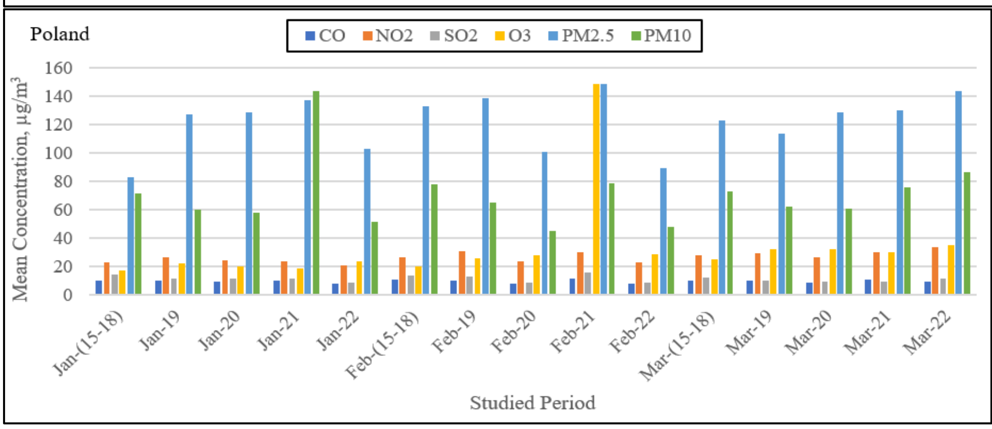

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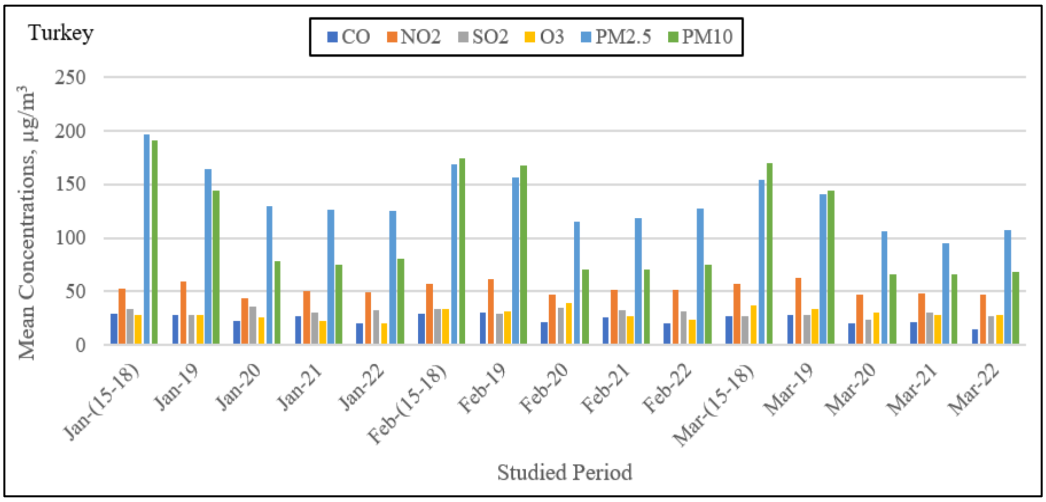

Fig. 4 Mean air pollutant concentrations of examined countries from the European continent.

In Spain, the lockdown was applied from March 2020 to June 2020 (Donzelli et al., 2021). CO showed the maximum decrease in its concentration for the examined months in 2022. Comparative analysis with baseline period also showed reductions in NO_2 (-57%), SO_2 (-46%), and PM_{10} (-15%) (see Figure 4-Spain). Donzelli et al. (2021) assessed the effects of lockdown measures on air quality and pollutant emissions in Valencia (Spain) between the period of restrictions in 2020 and the same period in 2019. The highest reductions in the PM_{10} and $PM_{2.5}$ levels were observed for the València Centre, València Avd Francia, and València Pista de Silla in which there was a decrease of 58%–42%, 56%–53%, and 60%–41% respectively. Moreover in 2020, NO_x, NO_2, and NO concentrations decreased by 37.4%–65.5%, 35.7%–67.7%, and 35.3%–63.5%, respectively.

In France, the lockdown restrictions were from 17 March 2020 to 11 May 2020 (Ikhlasse et al., 2021). An extremely remarkable decrease in CO concentrations, up to over 4500%, was observed for almost all periods under study. In general, all pollutants decreased compared to the baseline period: NO_2 (-53%), SO_2 (-62%), $PM_{2.5}$ (-24%), and PM_{10} (-10%) concentrations (see Figure 4-France). Ikhlasse et al. (2021) also observed that the maximum daily concentrations detected in different regions of France have decreased by 18.18%, 37.14%, 20.36%, 9.28%, 44.38%, 5.1%, and 44.38%, respectively, for the pollutants SO_2, NO_2, CO, C_6H_6, NO_x, $PM_{2.5}$, and PM_{10}.

In the United Kingdom, the national lockdown was started on 24th March 2020 due to the rapid increase in the confirmed cases (Jephcote et al., 2021). Pollutants mostly decreased compared to baseline period in March 2022 (-71%) for CO, February 2022 (-57%) for NO_2, February 2021 (-79.5) for SO_2, January 2021 for O_3 (-11%), February 2022 (-38%) for $PM_{2.5}$ and February 2022 (-49%) for PM_{10}. In addition, in March 2020, when the quarantine restrictions started, all parameter concentrations except Ozone showed decreasing trends (see Figure 4-The United Kingdom). Jephcote et al. (2021) investigated changes in air quality by comparing daily pollutant measurements of NO_2, O_3, and $PM_{2.5}$ during the lockdown period (from 30/03/2020 to 03/05/2020) with measurements over the same period in 2017-2019 for the United Kingdom. Measurements from 129 monitoring stations suggested mean reductions in NO_2 of 38.3% (-8.8 µg/m^3) and $PM_{2.5}$ of 16.5% (-2.2 µg/m^3). In contrast, O_3 concentrations had average increased by 7.6% (+4.8 µg/m^3).

In Croatia, the lockdown restrictions started on 16th March 2020 (Vidić et al., 2021). During these restrictions, NO_2, SO_2, and $PM_{2.5}$ concentrations exhibited reductions compared with the average values of the previous period at -37.9%, -18.6%, and -14%, respectively. SO_2 exhibited the highest reduction in its concentration in January 2021 (-169%), while CO concentration does not have any variation (see Figure 4-Croatia). Jakovljević et al. (2021) compared mass concentrations of the PM_1 particle fraction (particulate matter with an equivalent aerodynamic diameter < 1 µm) and polycyclic aromatic hydrocarbons

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(PAHs) in PM_1 and NO_2 during the lockdown period (March–May 2020) with those measured in the same period the year before. They found reductions in the concentrations of NO_2 and PM_1 particles by around 35% and by 26% for the total PAHs at the traffic measuring site.

In Poland, the lockdown applications were imposed on 12 March 2020 (Filonchyk et al., 2021). The maximum reduction for CO (-41%), NO_2 (-16%), $PM_{2.5}$ (-48%), and PM_{10} (-63%) was recorded in February 2022, while the highest decrease in SO_2 was observed in January 2022 (Figure 4-Poland). Decreases were also observed in pollutant concentrations (CO, NO_2, SO_2, PM_{10}) in March 2020, when containment policies started; moreover, the rates in March 2020 are compared to February, and the change of concentration of air pollutants suggested that lockdown measures did not mitigate air pollution. Filonchyk et al. (2021) investigated the concentrations of atmospheric pollutants (PM2.5, PM10, NO2, and SO2) in Poland and found that ground-based and satellite data demonstrated the reduction of air pollutants in the period of lockdown as compared to the same periods in 2018 and 2019. Finally, they concluded that restrictions imposed to prevent the spread of COVID-19 significantly improved Poland's air quality.

Finally, in Turkey, the government announced the first restrictions on March 12, 2020 (Orak and Ozdemir, 2021). In March 2020, variations in the concentrations of all air pollutants were: -36% for CO, -21% for NO_2, -14% for SO_2, -20% for O_3, -45% for $PM_{2.5}$, and -157% for PM_{10}, respectively (compared with the average values of the pre-pandemic period 2015-2018). Among these air pollutants, SO_2, O_3, and PM_{10} showed a tendency to decrease more in March 2020 compared to February also without lockdown measures. Except for February 2019, maximum reductions were recorded for PM_{10} pollutant concentration for all periods investigated (see Figure 4-Turkey). Orak and Ozdemir (2021) investigated the impact of lockdown measures on ambient air pollution and its association with human mobility in all cities of Turkey by comparing measurement data in 2020 with periods between January 2015 and November 2020. Results suggested that transit, and workplaces mobility were significantly correlated with PM_{10} and SO_2 concentration levels in Turkey.

As far as Oceania continent, changes in air pollutant concentrations are in Figure 5. In Australia, the lockdown started on 16 March 2020 (Duc et al., 2021). While all air pollutant concentrations, except $PM_{2.5}$ and PM_{10}, decreased in March 2020, the maximum reduction was by NO_2 with 106%, O_3 with 94%, and CO with 61%. When all investigated periods were compared with the average values of the pre-COVID-19 pandemic period, NO_2 showed the maximum decrease except for January-February 2020 and February 2021 (see Figure 5-Australia). Duc et al. (2021) investigated the lockdown impact on air quality in the metropolitan area of Sydney as well as in the rest of New South Wales (Australia). The results from both statistical analyses and modeling methods showed that NO_2, CO, and $PM_{2.5}$ levels decreased during the lockdown, instead O_3 increased. However, the change in the concentration levels was small considering the large reduction of ~30% in traffic volume.

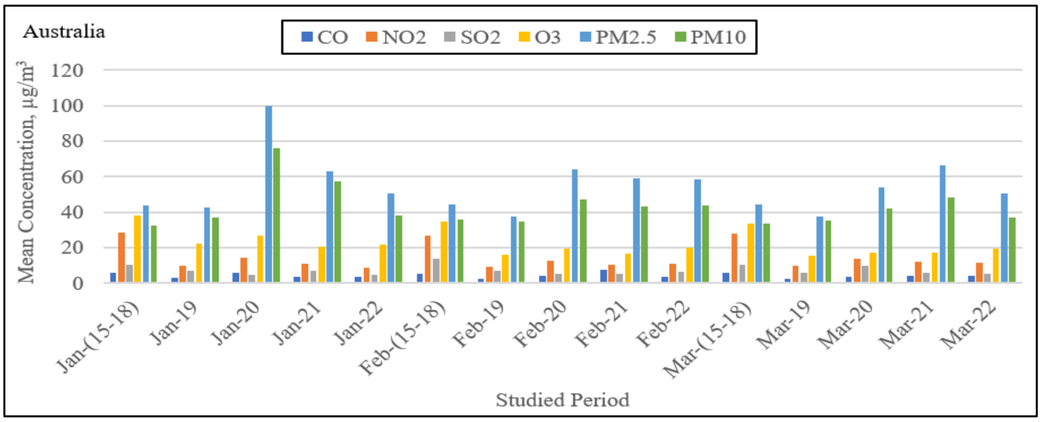

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Fig. 5 Mean air pollutant concentrations of Australia from the Oceania continent for the studied period.

3.2. General Observations

Considering the quarantine measures imposed, when the pollutant concentration is compared with the pre-COVID-19 periods for 19 countries examined in the study here, the maximum CO reduction was in France with a rate of 4,668% in January 2020, 2021, and 2022, followed by Canada with 1,010% in January 2019, 2021 and 2022. Comparative analysis showed that Australia and China have a maximum and equal decrease of 222% in January 2022 (Popescu and Ionel, 2010). Regarding the highest declining rate of SO_2, associated with both natural sources like volcanoes and anthropogenic sources, such as coal-burning power plants, smelters, and oil refineries, Canada (413%) in February 2021, Colombia (224%) in March 2021, and Germany (191%) in January 2022 were the top three ranked countries, respectively (Fioletov et al., 2015). The study here also shows that the country with the maximum decrease (-343%) in the change of ozone concentration at ground level (comparing values in the 2015-2018 period pre-COVID-19) is Colombia, which also showed a maximum decrease in NO_2 (-21%) and CO (-151%) concentrations. China and Australia showed a 121% decrease in the O_3 level, with significant reductions in NO_2 (-187%) and CO (-137%) in March 2019, which is the highest reduction rate in all periods under study here. Considering the countries with maximum declines in particulate matter emissions ($PM_{2.5}$ and PM_{10}), results show a decrease of 112% in Canada over March 2022 for $PM_{2.5}$, and a decrease of 159% in Turkey over March 2021 for PM_{10}.

To systematize the main findings of this study, Table 2 summarizes the main effects of lockdown policy on air pollution between different countries. Within the scope of the pandemic measures of the countries, the maximum reduction in CO emissions was recorded in India, Israel, Canada, France, Germany, and Spain, the minimum ones were in China, Poland, and Australia. Moreover, the maximum reduction in NO_2 emissions was observed only in China and Australia, whereas the minimum decrease was observed in Chile. Maximum reductions for SO_2 emissions were recorded in Japan, South Korea, America, Brazil, Croatia, Netherlands, Poland, and the United Kingdom, while minimum reductions were recorded in Croatia, Spain, and Turkey. In addition, no country recorded a maximum decrease in O_3 and $PM_{2.5}$ concentrations. The minimum decrease in O_3 concentrations was observed in Japan and Croatia, while Israel, South Korea, the Netherlands, and England were the countries where the minimum reduction was observed in $PM_{2.5}$ among air pollutants. As for PM_{10}, Colombia and Turkey were the countries representing the maximum decrease in its concentrations, instead, Canada, Brazil, America, France, and Germany are the countries showing the highest decrease in PM_{10} concentrations. Overall, when the maximum reduction in pollutant concentrations is evaluated in terms of amount, CO with a rate of 655.5% is superior to others, instead, if the sum of the countries is evaluated, SO_2 shows a decrease in nine different countries.

Findings show consistent evidence of a larger reduction of emissions in Europe, except the EU and the UK (-8.4%), followed by East Asia and the Pacific (-4.3%). Chossière et al. (2021) found that lockdowns led to reductions in NO_2 concentrations globally, using global satellite observations and ground measurements from 36 countries in Europe, North America, and East Asia. However, they stated that there were no reductions in $PM_{2.5}$ and ozone globally. Dang and Trinh (2021) investigated air quality for 164 countries before and after the COVID-19 lockdowns. They observed a decrease in the global concentration of NO_2 (-5%) and $PM_{2.5}$ (-4%). They suggest that lockdowns can improve air quality. Hammer et al. (2021) compared global $PM_{2.5}$ concentrations during the lockdown period from January to April 2020 with the same periods in 2018 to 2019 considering China, Europe, and North America using a combination of satellite data, simulation, and ground-based observations. They concluded that mean $PM_{2.5}$ concentrations during lockdowns changed in the range of −11 to −15 $\mu g/m^3$ for China, +1 to −2 $\mu g/m^3$ for Europe, and 0 to −2 $\mu g/m^3$ for North America.

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Table 2 Main effects of containment policy of lockdown on air pollutants between selected countries worldwide.

		Average variation % of air pollutant values from January 2019 to March 2022 compared with baseline period (2015-2018)					
Continent	Country	CO	NO_2	SO_2	O_3	$PM_{2.5}$	PM_{10}
Asia	China	-49.68	-153.77	-98.25	-87.26	17.10	20.89
	India	-105.90	-39.30	-17.20	-24.50	12.40	13.10
	Israel	-122.10	12.30	-13.80	33.30	-8.20	-18.80
	Japan	-24.50	-15.00	-37.50	-1.80	-12.30	-16.10
	South Korea	-26.70	-20.40	-64.70	5.90	-1.30	-12.90
North America	Canada	-655.50	-13.80	-193.70	4.50	-27.30	-8.10
	USA	-17.10	-7.60	-107.30	12.10	-4.30	-2.30
South America	Brazil	-48.50	-10.90	-89.00	4.70	8.60	-7.70
	Chile	4.30	-15.80	-24.40	6.70	8.60	16.70
	Colombia	-46.10	19.00	18.50	-29.30	-12.40	-46.30
Europe	Croatia	0.00	-8.10	-60.10	-0.02	-11.90	5.70
	France	-3471.8	-17.90	-33.50	3.60	-11.40	-1.80
	Germany	-135.00	-11.50	-92.20	9.80	-29.60	-1.60
	Netherlands	10.50	-16.00	-16.30	8.20	-4.50	-7.70
	Poland	-9.60	2.90	-24.30	27.30	7.00	-16.80
	Spain	-73.80	-22.20	-18.50	4.20	3.90	5.50
	Turkey	-27.60	-9.40	-4.40	-20.40	-39.50	-115.00
	United Kingdom	-19.40	-23.40	-26.20	7.20	-4.90	-7.00
Oceania	Australia	-59.80	-153.70	-98.30	-87.30	17.10	20.90

Note: For details see supplemental materials.

He et al. (2021) investigated variation in the concentration of $PM_{2.5}$, NO_2, and O_3 for pre- and post-lockdown periods at global, continental, and national scales by analyzing ground-based data from >10,000 monitoring stations in 380 cities worldwide. They found that concentrations of $PM_{2.5}$ and NO_2 decreased by 16.1% and 45.8%, respectively, whereas O_3 concentration during lockdown (March to May 2020) increased by 5.4% compared to the baseline period (2015–2019) at the global scale. At the continental scale, maximum reductions for $PM_{2.5}$, NO_2, and O_3 were observed in East Asia (-20.4%), Europe (-42.5%), and North America (-7.8%), respectively. On the national scale, they found maximum reductions of 50.8 % for $PM_{2.5}$ in India and 103.5% for NO_2 in Spain, as well as 22.5% for O_3 in India. Kumari and Toshniwal (2020) analyzed the variations in the concentration of $PM_{2.5}$, PM_{10}, NO_2, SO_2, and O_3 during the pre-lockdown and post-lockdown phase from 162 monitoring stations from 12 cities across the globe. They showed that the concentrations of $PM_{2.5}$, PM_{10}, and NO_2 were reduced by 20–34%, 24–47%, and 32–64%, respectively, because of reduced anthropogenic emission sources associated with lockdown, whereas a lower reduction in SO_2 was observed because of functional power plants. In contrast to decreasing in the concentration of the air pollutants, except for ozone, because of reductions in the primary pollutant of NO_x emissions, the O_3 concentration increased. Torkmahalleh et al. (2021) assessed the impacts of COVID-19 lockdowns on ground-level $PM_{2.5}$, NO_2, and O_3 concentrations on a global scale using data from 34 countries, 141 cities, and 458 air monitoring stations on 5 continents (few data from Africa). Results showed a 34.0% reduction in NO_2 concentration and a 15.0% reduction in $PM_{2.5}$ during the strict lockdown period (until April 30, 2020). Instead, global average O_3 concentration increased by 86.0% during the same period.

Overall, then, results of the study here, using update data, are consistent with previous studies leading to the main findings that containment policies to cope with the rapid diffusion of COVID-19, they also reduce air pollution, improving temporarily air quality and environment with benefits for public health.

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4. Conclusions

Figure 6 show that measures of control, such as lockdown, to reduce rapid transmission of SARS-CoV-2 and cope with COVID-19 pandemic crisis have pros and cons (Coccia, 2021d): they reduce, whenever possible, transmission dynamics and air pollution, but they have also negative consequences on socioeconomic system (Coccia, 2021c, 2022b, 2022c; Ray et al., 2022; Mousazadeh et al., 2021; Filonchyk et al., 2020; Le Quéré et al.,2020)

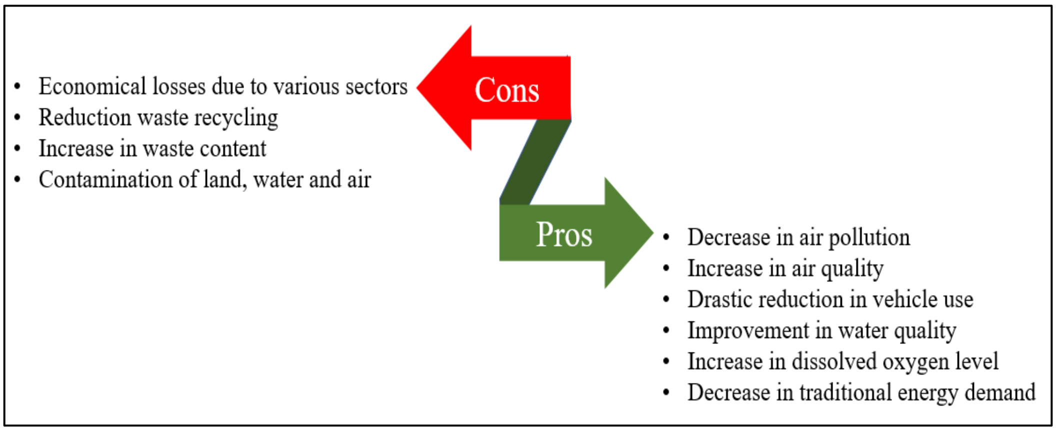

Fig. 6 Pros and cons of COVID-19 lockdown restrictions on environment.

While strict lockdown measures imposed by the governments to combat the transmission of COVID-19 impact the countries' economies adversely, they can also improve air quality by reducing greenhouse gas emissions and air pollutants based on anthropogenic sources (Ray et al. 2022). Results suggested that the COVID-19 control measures imposed by countries' governments brought about a substantial decline in the concentration of air pollutants in contrast to pre-lockdown periods. It has been observed that the countries showed a greater decrease in air pollutant concentrations in March 2020, when they imposed mostly full lockdown. Findings here revealed that the effects of national restrictions on air quality vary significantly between countries. In fact, in March 2020, the countries that showed the maximum reduction in pollutant concentrations are: CO (-4,367.5%) in France, NO_2 (-150.5%) in China and Australia, SO_2 (-154.1%) in Israel, O_3 (-94.1%) in China, $PM_{2.5}$ (-41.4%) in Germany and PM_{10} (-157.4%) in Turkey. In general, the observed improvements in air quality differ between regions may be due to the different geoeconomic, environmental, climate and demographic characteristics (Siciliano et al., 2020).

Most of the studies done so far were on how various strict measures of control taken by governments to mitigate /stop the spread of COVID-19 affect the air pollution in region, comparing the primary and secondary air pollutant concentration values obtained from air quality monitoring stations with data of previous years. The majority of the results obtained are that the concentrations of air pollutants substantially decrease during the lockdown, while the ozone concentration generally increases due to the decrease in nitrogen dioxide emissions, especially from motor vehicles and industrial activities. This study shows consistent results with previous literature and extends knowledge on important and drastic interventions to reduce air pollutants and improve air quality and environment. However, a study by Jakob et al. (2022) stated that the decrease in pollutant concentrations observed is not related to the restrictive measures for COVID-19 but is associated with seasonal changes.

Although this study has provided interesting results, that are of course tentative, it has also limitations. First, seasonal variations in the pollutant concentration are not comprehensive because of the unavailability of data for many countries. Second, not all confounding factors that affect the air pollution are taken into consideration during measures of control and in future studies these factors have to be analyzed for supporting results here. Finally, the extension of the period under study and update of data are needed to reinforce results of statistical analyses to truly warrant policy conclusions for crisis management of next pandemics.

Overall, then, the public policy of countries, to cope with next pandemics and epidemics, should be based on different factors that are not only parameters related to medicine but also to social, economic, sustainable, environmental and innovation science. Hence, the design of a comprehensive and multidisciplinary strategy of containment, based on a good governance, can increase the effectiveness of policy responses to face next pandemic crisis and also generate environmental advantages (Benati and Coccia, 2022; Coccia, 2021e, 2022d, 2022e; Farazmand, 2001, 2014).

Hence, measures of control for COVID-19 affect air quality and in general environment and they should be designed considering manifold aspects included economic and social ones (Barbier and Burgess, 2020; Rume and Islam, 2020).

In this context, considering the expectations that containment measures will play a critical role in determining future policy actions to cope with next pandemic threats, next studies can analyze the effects of containment policies on environment also examining how air pollutant concentrations change seasonally in the long term. To conclude, socioeconomic and environmental factors should shape and support a general public policy of containment based on good governance, high investments, and new technology to improve the preparedness of nations to face future pandemic threats and support sustainability.

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and material: The datasets during the current study are available from the author on reasonable request.

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