

# Air Quality Transformation in Twelve Major Cities during Covid-19 Lockdowns: A Global Assessment

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**Abstract** - The implementation of lockdown measures worldwide, aimed at preventing the spread of Covid-19, has temporarily improved air quality. This research paper aims to examine the impact of the lockdown period from March to May 2020 on the levels of four common air pollutants in 12 major cities, namely Delhi (India), Newcastle (UK), California (USA), Brescia (Italy), São Paulo (Brazil), Langfang (China), Madrid (Spain), Khon Kaen (Thailand), Santiago (Chile), Bogota (Colombia), Wellington (New Zealand), and Silivri (Turkey). The study analyzed the changes in average monthly concentrations of nitrogen dioxide (NO<sub>2</sub>), ozone (O<sub>3</sub>), and particulate matter (PM<sub>10</sub> and PM<sub>2.5</sub>) during two phases: the pre-lockdown and lockdown phases. During the lockdown, all air pollutants except ozone exhibited a significant decrease. These results highlight the positive impact of reducing anthropogenic emissions on air quality during the Covid-19 lockdown. The researchers also used principal components analysis to examine the concentrations of NO<sub>2</sub>, O<sub>3</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> from January 2018 to June 2020. The findings revealed that the 11 monitoring sites in the cities could be grouped into six clusters based on similar air pollution patterns. Overall, this study provides valuable insights that can inspire policymakers and stakeholders involved in air quality management to implement changes in environmental policies. By targeting pollution sources, it is possible to mitigate the harmful effects of air pollutants.

**Keywords** - Covid-19; Air quality; Lockdown; Air pollutants; Principal components analysis

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## 1- Introduction

The outbreak of the novel COVID-19 (also referred to as Severe Acute Respiratory Syndrome Coronavirus 2; SARS-CoV-2) originated in Wuhan in December 2019 and has subsequently spread rapidly to various parts of the world [1, 2]. In excess of 26 million cases of the viral infection with greater than eight hundred sixty-three thousand associated deaths were reported globally, with the highest number of infections and fatalities reported in the United States of America (6,113,510 and 185,720), followed by; Brazil (3,997,865 and 123,780), Italy (271,515 and 35,497), India (3,853,406 and 67,376), Spain (479,554 and 29,194), Russia (1,001,965 and 17,365) and the United Kingdom (338,676 and 16,396) [3-5]. The Organization for Economic Cooperation and Development (OECD) has described the pandemic as the biggest threat to the global economy since the 2008

financial crises [6] impacting upon health, education, economy and environment, all continuing to unfold internationally [7]. The spread of the pandemic has substantially impacted upon the world's inhabitants and ecosystems [8]. For example, anthropogenic activities such as; industrialization, transportation, solid and plastic waste generation, excess wastewater generation and the formation of carbon monoxide (CO) abruptly reduced, perhaps for the first time in the modern history [9]. Moreover, these fundamental activities release air pollutants such as Particulate Matter 2.5 (PM<sub>2.5</sub>), Particulate Matter 10 (PM<sub>10</sub>), Ozone (O<sub>3</sub>), Nitrogen dioxide (NO<sub>2</sub>) and Sulfur dioxide (SO<sub>2</sub>) which have deleterious effects on the overall environment and particularly human health [10, 11]. They may cause or contribute to short- and long-term minor to severe respiratory illnesses, followed by an increase mortality ratio [12-14].

According to the World Health Organization, 4.6 million people die annually from diseases and illnesses directly linked to air pollution [15]. The term particulate matter (PM) describes the mixture of liquid droplets and solid particles suspended in air, with major components including; nitrates, sodium chloride, ammonia, black carbon, mineral dust, water and sulfate. These either can occur naturally or are manufactured. PM is usually emitted in the process of liquid or solid fuels combustion in order to generate power for motor vehicles and airplane engines, construction sites, unpaved road, and factories. PM differs in size, based on the width or diameter of the particles.  $PM_{2.5}$  and  $PM_{10}$  infers a particle diameter that is less than  $2.5\ \mu m$  and less than  $10\ \mu m$ , respectively. The quality of air can be measured by the presence PM in terms of mass per cubic meter of air volume ( $\mu g/m^3$ ). PM with associated particle size of  $<10$  and  $<2.5\ \mu m$  can easily be inhaled during normal tidal breathing and lodge within the lungs. Notably,  $PM_{2.5}$  is able to achieve deep lung deposition and hence enter blood circulation. PM are major risk factor for non-communicable diseases (NCD), including; lung cancers, chronic respiratory diseases and cardiovascular diseases (CVDs), According to the World Health organization (WHO), outdoor air pollution contributes to premature mortality in 58% of CVDs, 18% of respiratory diseases and 6% of lung cancer [16]. The WHO air quality guidance specifies that the annual and 24h averages of  $PM_{2.5}$  should not increase above  $10\ \mu g/m^3$  and  $25\ \mu g/m^3$  respectively [17]. The latter guidance specify that  $PM_{10}$  should not exceed an annual average of  $20\ \mu g/m^3$  and 24h average of  $50\ \mu g/m^3$  [18].

Similar to PM formation, the principle sources of  $NO_2$  and  $SO_2$  are combustion processes that include engines in ships, vehicles, power generators and heating. The current WHO guidelines indicate that for  $NO_2$ , the annual mean value should not exceed  $40\ \mu g/m^3$ . Higher values of  $NO_2$  are associated with causing bronchitis in asthmatic patients, whereas  $SO_2$  impacts upon the respiratory, cardiovascular and eye systems [17]. Ozone gas ( $O_3$ ) is formed by a photochemical reaction between sunlight and pollutants (such as  $NO_2$ ). According to the WHO air quality guidelines,  $O_3$  concentration should not exceed  $100\ \mu g/m^3$  for the mean value of over 8h, as the excessive concentrations may affect human health (i.e. reduce lung function, result in breathing difficulties, cause lung diseases and trigger asthma) [17].

To containing the virus, governments reacted typically with strict containment and mitigation policies to diminish human interaction [18]. The mandatory lockdown and border closures have led to a reduction in air pollution from industries, vehicle emissions and transportation sources [19]. The decline in air

pollution may also reduce cardiovascular and respiratory diseases [20, 21]. The reduction in air pollution during the lockdown period provided a window for improvement in air quality, giving environmentalists and policymakers an opportunity to highlight the positive impact of controlling pollution whilst developing achievable plans to sustain the drop observed. Accordingly, the COVID-19 outbreak may be considered as an indirect consequence of global environmental changes. In this instance, COVID-19 may be able to play a major and crucial role in what can be considered as the first step in changing global environment.

In the present paper, we have examined the positive impact of activities reductions resulting from the spread of COVID-19 on air quality in twelve cities across the globe with varied geographical conditions/environments. We have conducted a principal component analysis along with correlation maps and descriptive statistics on the concentrations of four air pollutants ( $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_2$ , and  $O_3$ ). The selected cities include; Bogota in Colombia, Brescia in Italy, California in USA, Delhi in India, Khonkaen in Thailand, Langfang in China, Madrid in Spain, Newcastle in UK, Santiago in Chile, Sao Paulo in Brazil and Silvri in Turkey, where partial or complete lockdown and quarantine were implemented.

## 2- Methodology

To study the changes in air quality during the lockdown period, data from eleven cities covering different regions were analyzed, i.e. Delhi (India), Newcastle (UK), California (USA), Brescia (Italy), São Paulo (Brazil), Langfang (China), Madrid (Spain), Khon Kaen (Thailand), Santiago (Chile), Bogota (Colombia) and Silivri (Turkey).

Characteristics related to these locations are summarized in Table 1. Concentrations of the different air pollutants for the time period of January 1st to May 30th from 2018 to 2020 were collected and analyzed. The data covered the air quality status before and during the Covid-19 lockdown. The hourly concentrations of the four major air pollutants including particulate matter ( $PM_{2.5}$  and  $PM_{10}$ ), nitrogen dioxide ( $NO_2$ ) and ozone ( $O_3$ ) were obtained from the local and regional agencies in charge of air monitoring stations. These are: India Meteorological Department (IMD) – India Central Pollution Control Board (CPCB), UK-AIR, air quality information resource - Defra / UK, Turkey National Air Quality Monitoring Network, Regional Agency for the Protection of the Environment of Lombardy / Italy and Air Resources Board (CARB) - Air Now - US EPA, CETESB-Environmental Company of the State of Sao Paulo, Hebei Province Environment Protection Agency, National Air Quality System in Chile, The

Environmental Observatory of Bogotá, Air Quality in Madrid, Atmosphere Protection Service - European Environment Agency, Division of Air Quality Data, Air Quality and Noise Management Bureau, Pollution Control Department / Thailand.

For each city, the monthly average concentrations of NO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> and O<sub>3</sub> during the lockdown period in 2020 were calculated and compared with the

monthly average concentration during the equivalent time period over the two previous years (2018–2019). The daily data of the four parameters (NO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub> and O<sub>3</sub>) were exported in Matlab 2019 where descriptive statistics and multivariate data analysis were applied. For descriptive statistics, then the changes in pollutants were evaluated between 2018, 2019 and 2020 considering them as three independent groups.

Table 1: Main characteristics of cities under investigation.

City / Country / Continent	Population	Climate	Area (Km <sup>2</sup> )	Start of lockdown
Brescia / Italy/ Europe	200,000	Humid subtropical	90.3	March 9
Delhi / India/ Asia	30,290,936	Between monsoon-influenced humid subtropical and semi-arid	1,484	March 22
Newcastle / UK/ Europe	809,000	Oceanic, with quite cold, rainy winters and mild, relatively rainy summers	114	March 23
Silivri / Turkey/ Asia	182,000	Warm and temperate	760	March 11
Yubba / Sutter / California / USA	64,925	Mediterran	38.79	March 22
Bogota / Colombia / South America	7,674,366	Moderate sea climate with dry warm summers and mild winters	1,775	March 25
Khon Kaen / Thailand / Asia	1,728,900	Tropical savanna	10,886	March 26
Langfang / China / Asia	4,795,000	Cold and temperate	6,417	Jan 23
Madrid / Spain / Europe	3,266,126	Quite arid and moderately continental, with relatively cold winters and hot summers	606	March 14
Santiago / Chile / South America	5,995,995	Warm and temperate	2,030	March 26
Sao Paulo / Brazil / South America	22,000,000	Monsoon-influenced subtropical humid	1,521	March 24

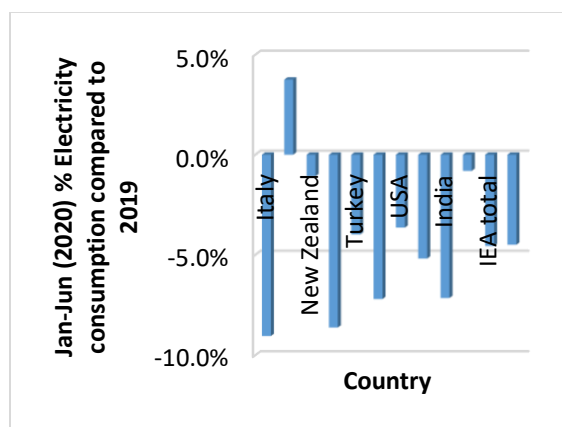
The suitability of data for normal distribution was examined using Shapiro-Wilks test. As the groups did not show normal distribution median, interquartile range (IQR) was calculated. To compare the groups Mann Whitney U test was used where significance was evaluated at a p value below 0.05. To compare the

differences between the cities' profiles both correlation and principal component analysis (PCA) methods were used. For correlation, 0.95 was taken as a threshold for the correlation coefficient (r) value. For PCA, clustering between difference cities profiles were examined.

### 3- Results and Discussion

#### 3.1- Link between transportation, energy use and emissions

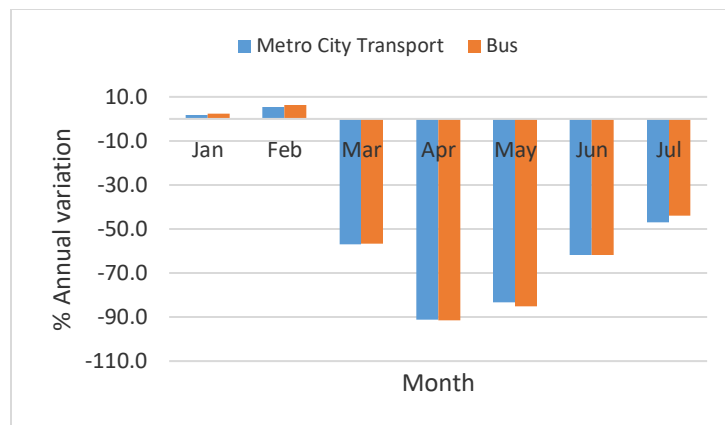
To thoroughly investigate the impact of the Covid-19 pandemic on air quality, it is essential to consider the connection between activities that generate emissions, such as transportation and energy consumption, and the concentrations of air pollutants. According to the International Energy Agency [22], road transport and energy production and consumption are significant contributors to air pollution on a global scale. The outbreak of the Covid-19 pandemic has led to widespread lockdown measures, resulting in a remarkable shift in people's daily routines. As a consequence, there has been a substantial reduction in overall electricity consumption and a virtual halt in transportation systems within the affected areas [23]. Data presented in Figure 1 indicates a noteworthy decline in total electricity consumption during the first half of 2020 when compared to the same period in 2019. For instance, India witnessed a reduction of at least 7.2%, Italy experienced a decrease of 9.0%, Spain saw an 8.6% drop, the United Kingdom recorded a decline of 7.2%, and the USA observed a decrease of 3.6% [24]. Similarly, the transportation sector has been significantly impacted by the Covid-19 pandemic. By the end of March 2020, global road transport activity had plummeted to nearly 50% below the average levels of 2019 [24, 25].



**Fig. 1** Electricity consumption during the first six months of 2020 as compared to 2019.

The number of travelers using both metro and bus transport has dwindled across all cities. For instance, strict lockdown measures in Madrid, Spain, led to a

substantial decline in transportation usage. In April 2020, there was a staggering decrease of 91.2% in Metro ridership and a 91.5% decrease in bus ridership compared to the same month in 2019, as illustrated in Figure 2 [26].



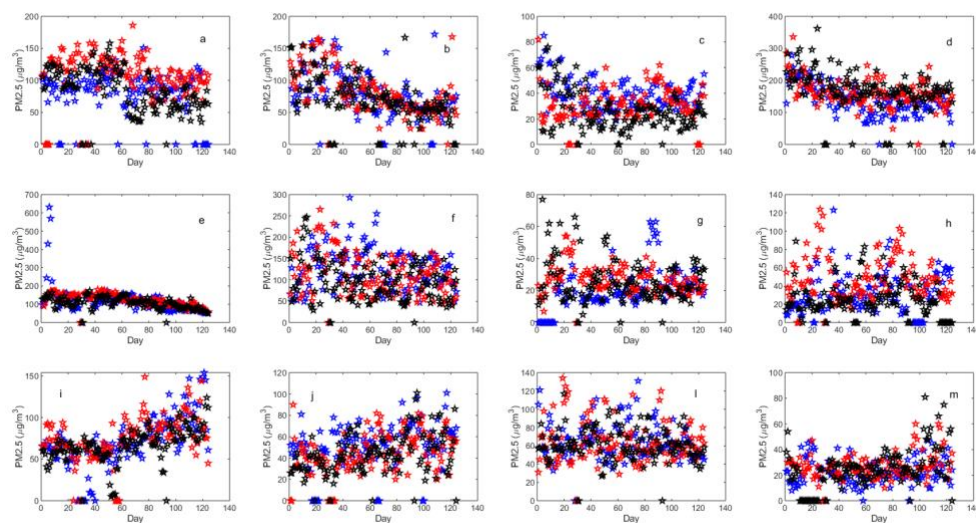
**Fig. 2** Annual variation in metro and bus transportation in Madrid/Spain in 2020 as compared to 2019.

The reductions in energy consumption and road transportation during the Covid-19 pandemic have directly contributed to a decrease in emissions within the affected areas. The subsequent section will delve into a detailed discussion of these emission reductions.

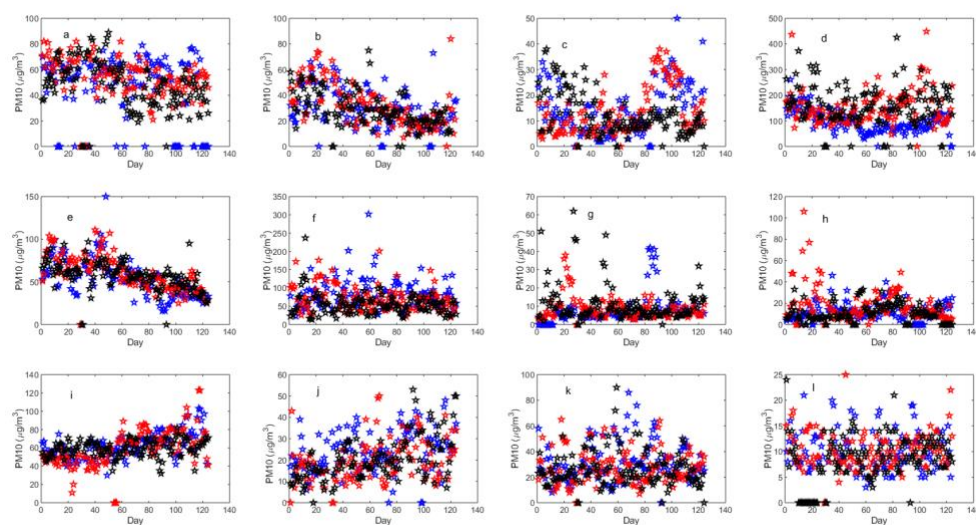
#### 3.2- Effect of Covid-19 on air quality

The role of viruses extends beyond epidemics and pandemics, and scientists now suggest that they have played a significant role in shaping the evolution of life on Earth. Interestingly, the current viral pandemic may also influence our approach to addressing one of the most pressing environmental challenges of the modern post-industrial era: air pollution.

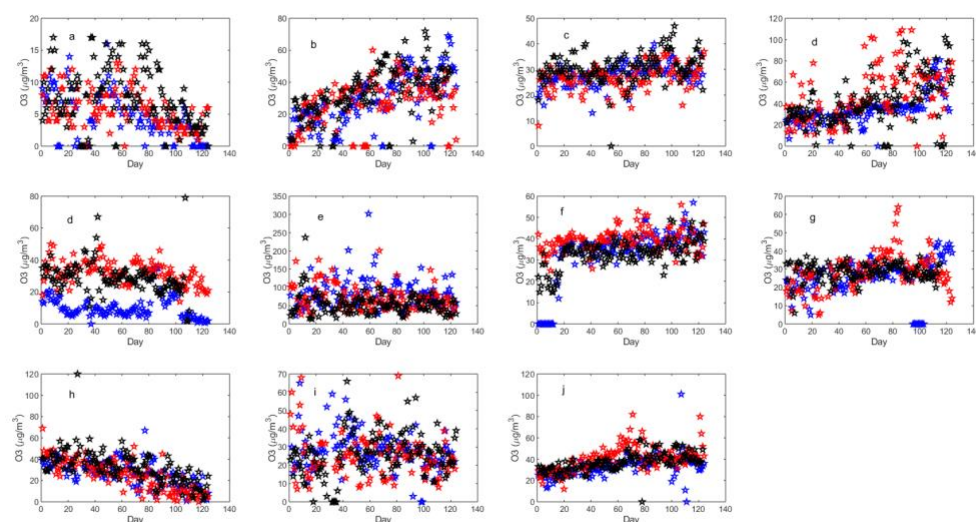
In March 2020, various cities worldwide implemented full or partial lockdown measures in response to the Covid-19 pandemic. These cities experienced diverse effects due to the virus. The findings of this study reveal variations in the 24-hour concentrations of major air pollutants (PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, and O<sub>3</sub>) across different locations and countries before and during the lockdown (Figs. 3-6). Notably, there was a substantial decrease in air pollutant concentrations during the lockdown, indicating a temporary positive impact of Covid-19 on the environment.



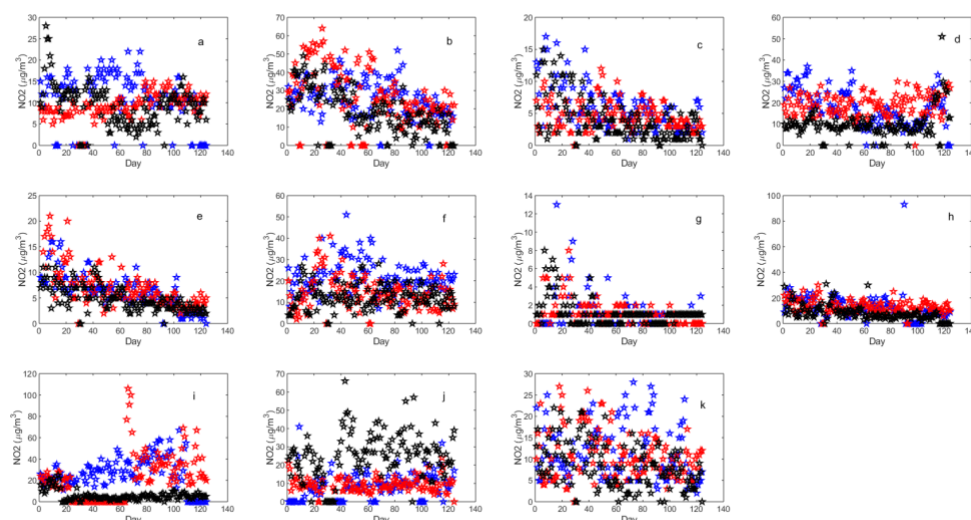
**Fig. 3** Daily change of PM2.5 between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM2.5 for (a) Bogota, (b) Brescia Villagio Sero, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i) Santiago, (j) Sao Paulo, (k) Silvri and (l) St Willington.



**Fig. 4** Daily change of PM<sub>10</sub> between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM<sub>2.5</sub> for (a) Bogota, (b) Brescia Villagio Sero, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i) Santiago, (j) Sao Paulo, (k) Silvri and (l) St Willington.



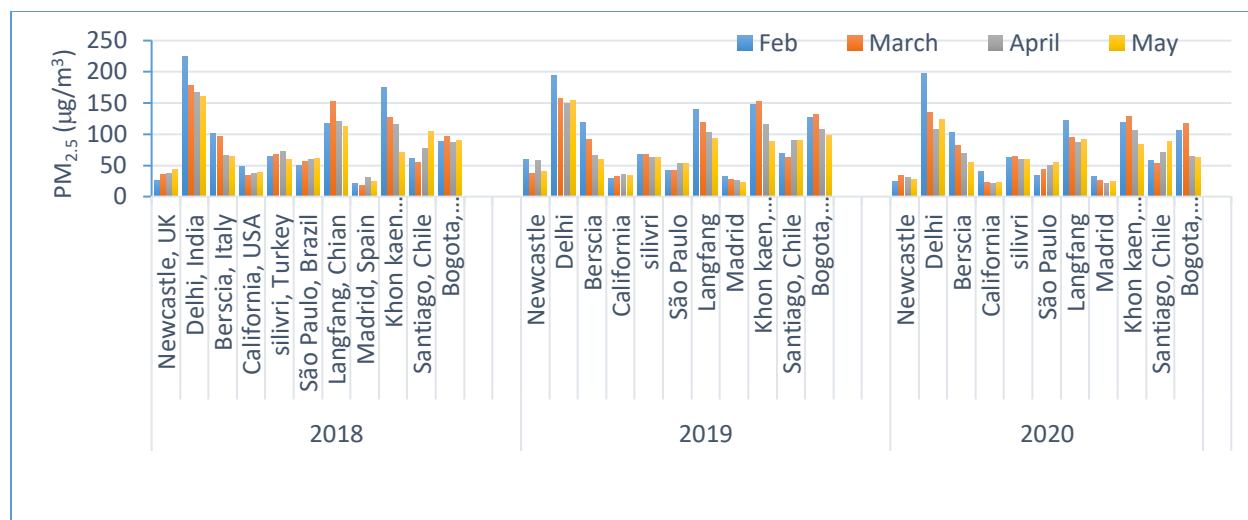
**Fig. 5** Daily change of O<sub>3</sub> between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM<sub>2.5</sub> for (a) Bogota, (b) Brescia Villagio Sero, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i) Santiago, (j) Sao Paulo and (k) Silvri.



**Fig. 6** Daily change of  $\text{NO}_2$  between March and May 2018 (blue), 2019 (red) and 2020 (black) for  $\text{PM}_{2.5}$  for (a) Bogota, (b) Brescia Villagio Sero, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i) Santiago, (j) Sao Paulo and (k) Silvri.

Figure 7 illustrates the changes in  $\text{PM}_{2.5}$  concentrations before and during the lockdown in eleven cities. Almost all cities demonstrated a reduction in  $\text{PM}_{2.5}$  concentrations during the lockdown, with significant decreases observed in Delhi, Newcastle, and California. According to the World Health Organization [16], the standard limit for  $\text{PM}_{2.5}$  is  $25 \mu\text{g}/\text{m}^3$ . Prior to the lockdown, the monthly average  $\text{PM}_{2.5}$  concentration in all cities exceeded this limit. However, during the lockdown,  $\text{PM}_{2.5}$  concentrations in all cities substantially decreased (Fig. 7), except for California and Madrid, where the average concentration remained below the WHO standard

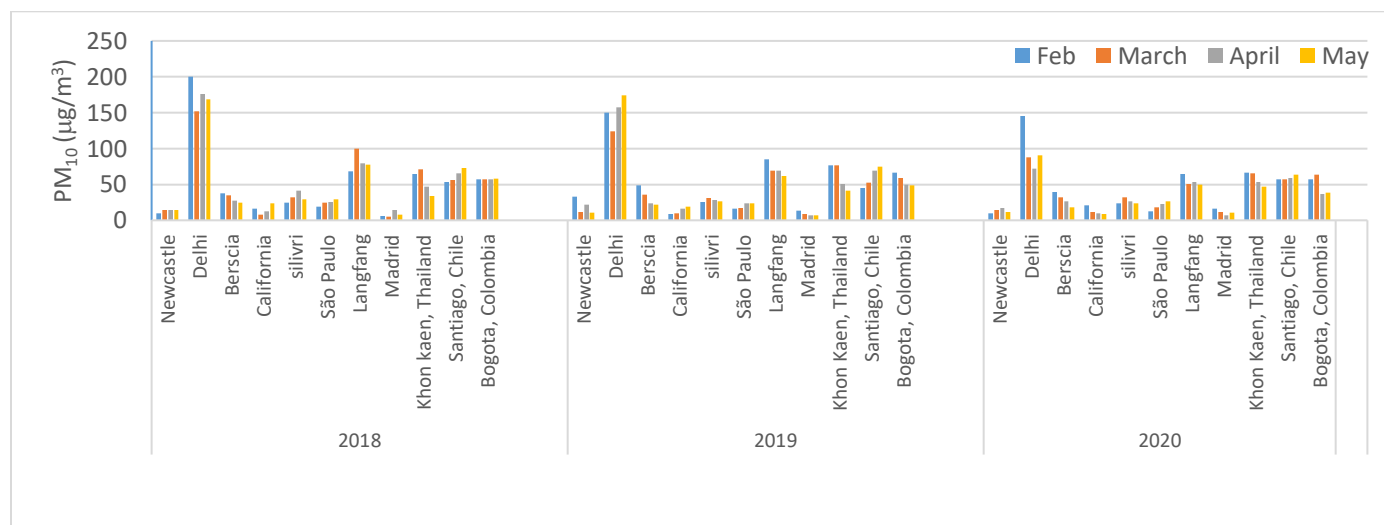
limit. Newcastle exhibited the highest reduction in  $\text{PM}_{2.5}$ , with a decrease of 59.7% during February 2020 compared to 2019 ( $[\text{PM}_{2.5}]_{\text{Before}} = 59.56 \mu\text{g}/\text{m}^3$ ;  $[\text{PM}_{2.5}]_{\text{During lockdown}} = 24.0 \mu\text{g}/\text{m}^3$ ). The reductions ranged from 6.3% to 59.7%, -2.4% to 27.7%, -5.7% to 14.0%, -37.9% to 39.5%, 15.8% to 23.1%, 3.5% to 8.14%, -3.8% to 19.3%, 2.1% to 20.3%, -8.7% to 17.4%, 4.7% to 19.8%, 2.3% to 21.8%, and 11.4% to 40.2% for Newcastle, Delhi, Brescia, California, and Silvri, respectively.



**Fig. 7** Variations of  $PM_{2.5}$  concentrations during 2018, 2019 and 2020 for February-May in Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

Concerning  $PM_{10}$ , there was a noticeable reduction in concentrations across all investigated cities (Fig. 8). This can be attributed to the significant decrease in vehicular traffic and industrial activities during the lockdown period. Newcastle and Delhi experienced the most substantial drops in  $PM_{10}$  concentrations,

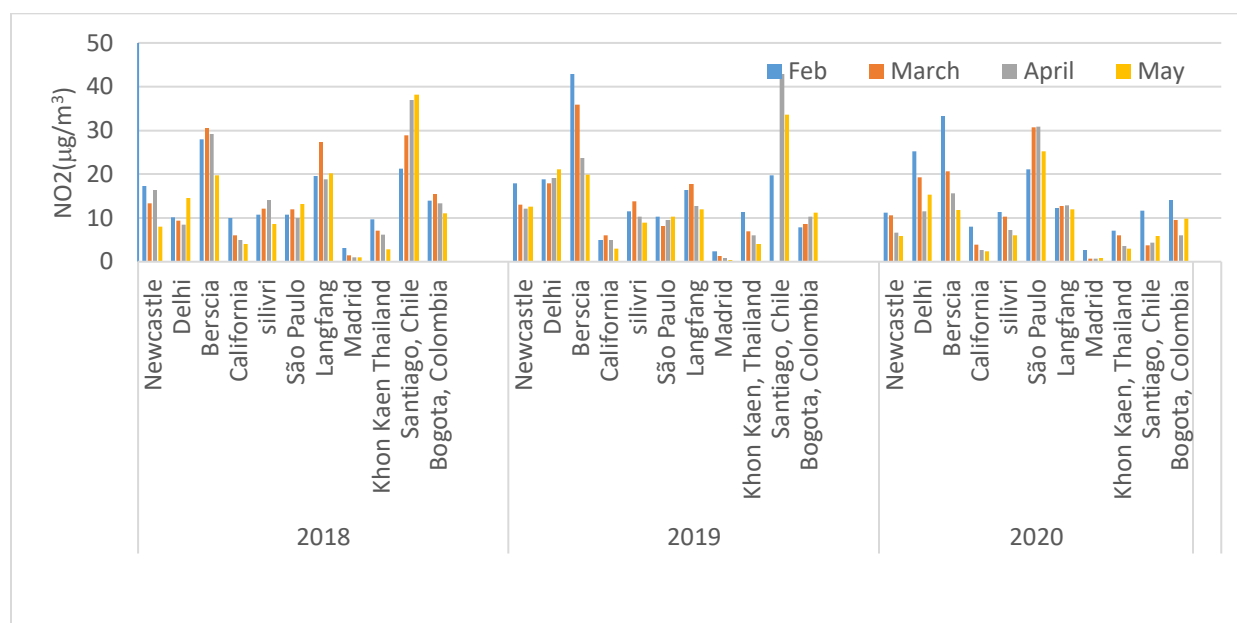
with reductions of 71.3% and 54.3% respectively during specific months compared to the previous year. California also witnessed declines of 42.4% and 52.3% in April and May 2020, respectively, compared to the same months in 2019.



**Fig. 8** Variations of  $PM_{10}$  concentrations during 2018, 2019 and 2020 for February-May Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

Figure 9 depicts the trends in  $NO_2$  emissions before and during the lockdown in the eleven cities. It is evident that  $NO_2$  emissions significantly reduced in all cities, except for Delhi, where  $NO_2$  levels increased during February and March 2020. Newcastle saw a noteworthy reduction of 53% in  $NO_2$  emissions during May 2020 compared to May 2019. Brescia

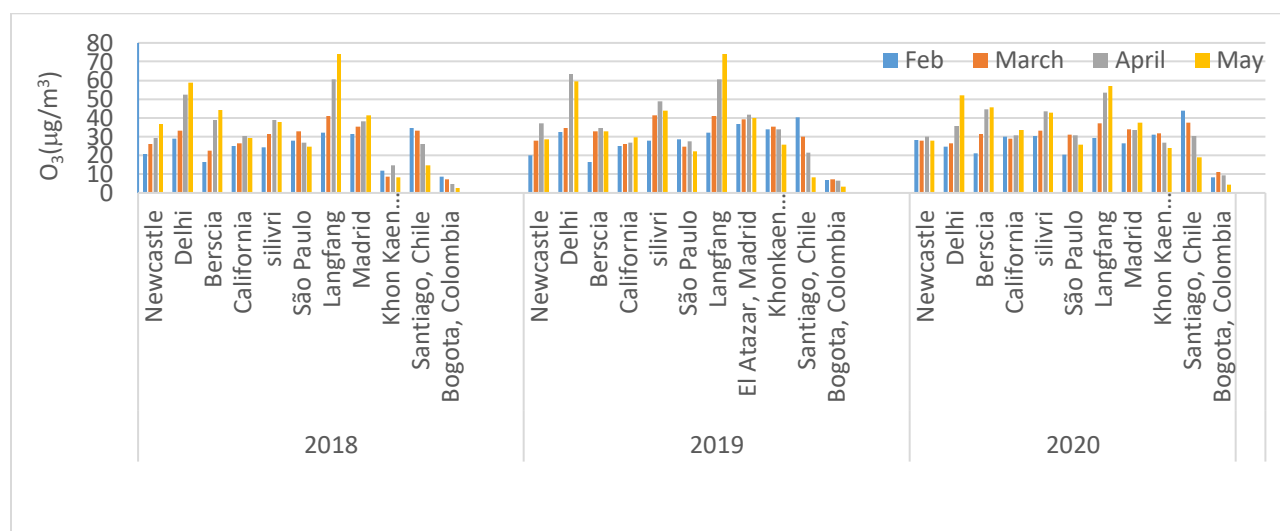
experienced a reduction of up to 42% in  $NO_2$  concentrations during the lockdown in March 2020 compared to March 2019. The highest reduction in California, 46.9%, occurred in April 2020 when compared to April 2019. The temporary decline in  $NO_2$  concentrations highlights the impact of human activities on global air quality.



**Fig. 9** Variations of  $\text{NO}_2$  concentrations during 2018, 2019 and 2020 for February-May in Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

Regarding  $\text{O}_3$ , concentrations increased in Silivri, Brescia, São Paulo, and Santiago, while they decreased in Delhi, Madrid, and Khon Kaen during the lockdown, despite the decrease in  $\text{NO}_2$  levels (Fig. 10). The increase in  $\text{O}_3$  levels in these cities may be attributed to photochemical reactions involving ozone precursors ( $\text{NO}_x$ ) under favorable weather conditions for  $\text{O}_3$  production [27]. As  $\text{O}_3$  gas is not directly

emitted into the atmosphere but formed through the presence of  $\text{NO}_x$ , volatile organic compounds (VOCs), and solar radiation, there are complex factors beyond emissions alone that influence  $\text{O}_3$  concentrations. Therefore, the influence of meteorology on the variation of  $\text{O}_3$  concentrations should also be examined.



**Fig. 10** Variations of  $\text{O}_3$  concentrations during 2018, 2019 and 2020 for February-May in Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

Overall, the analysis of air pollutant concentrations during the Covid-19 lockdown period provides valuable insights into the short-term improvements in air quality. These findings underscore the potential for addressing the silent killer, air pollution, by taking cues from the current viral pandemic and implementing effective strategies and policies to reduce emissions and protect the environment and human health.

### 3.3- Statistical and Principal Component Analyses

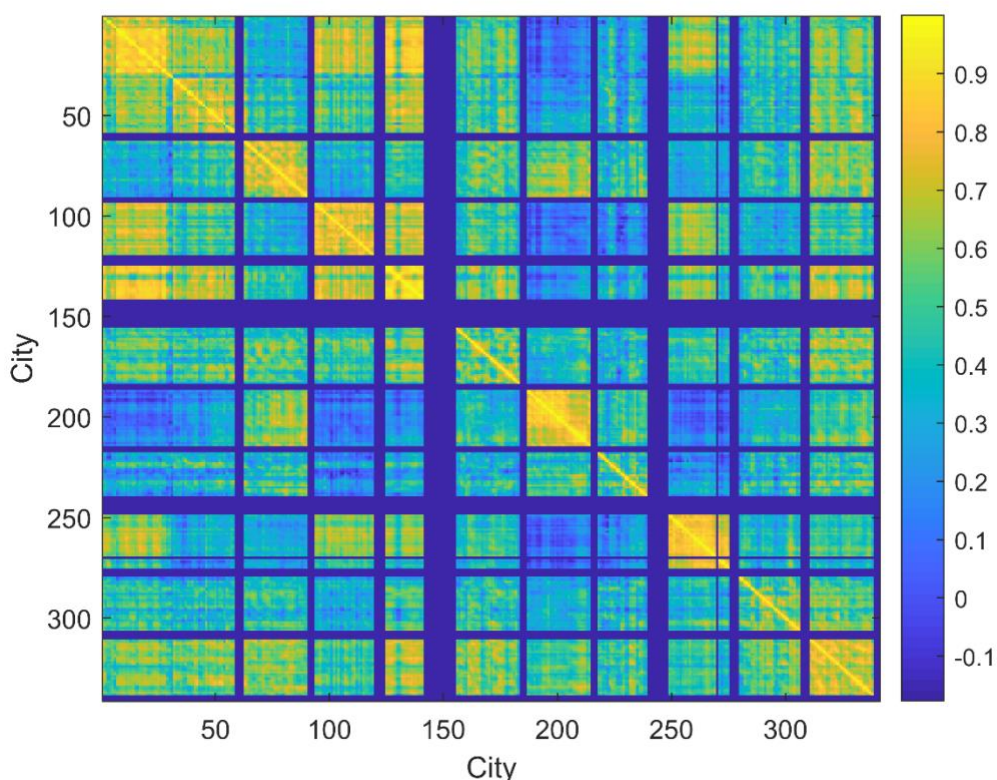
Descriptive statistics of the four air pollutants studied in eleven cities have been carried out. A statistical

summary of these data is given in Table 2. As can be seen, the lowest concentration recorded for PM<sub>2.5</sub> is 0.0 µg/m<sup>3</sup> at Sao Paulo in 2020 and the lowest concentrations recorded for each of PM<sub>10</sub>, O<sub>3</sub> and NO<sub>2</sub> are 0.0 µg/m<sup>3</sup> at Bogota in 2018. On the other hand, the highest concentrations obtained for PM<sub>2.5</sub>, PM<sub>10</sub>, O<sub>3</sub> and NO<sub>2</sub> are 244 at Khon Kaen in 2018, 160 µg/m<sup>3</sup> at Delhi in 2020, 140 at Langfang in 2018 and 93 µg/m<sup>3</sup> at Newcastle in 2020 respectively. These exceeded the WHO daily average limit for the human health protection established as 25, 50, and 50 µg/m<sup>3</sup> for PM<sub>2.5</sub>, PM<sub>10</sub> and NO<sub>2</sub> respectively.

Table 2: Summary of the descriptive statistics applied over the three years, 2018-2019.

City	Parameter	PM2.5			PM10			Ozone			Nitrogen dioxide		
		2018	2019	2020	2018	2019	2020	2018	2019	2020	2018	2019	2020
Bogota	Median	81.5	112	86	44.8	53.1	46.8	5	5.75	8	13	15	12
	Min-Max	14.5-102	56-133	47.3-103.3	0-65	21.7-63.5	18.8-59	0-7.5	1.5-9	1.5-10.8	0-18	0-20	0-22
	IQR	69.3-90.7	99.8-119	77.2-93.1	40.6-54.1	48.6-58.9	43.4-53.3	3.81-5.69	4.75-6.44	6.31-9.19	2.25-15	11-17.8	10-1
Brescia	Median	78.5	83.3	71.3	29.4	32.1	28.1	29	27.7	35	27	33	29
	Min-Max	37-101	36.3-108	13.8-102	18-41.5	18.5-42.3	12-39	12.5-46.5	12-36.5	18.3-43.8	0-39	14-47	0-52
	IQR	59.9-84.8	65.6-91.4	60.2-82.3	24.3-34.2	27.1-36.8	24.5-32.7	22-36.4	24.3-31.6	31.1-37.9	21.3-31.8	22.3-37.5	18-3
California	Median	38	30	26.5	14.3	13	12.1	28	27.5	30.8	9	6	5
	Min-Max	25-54	17.3-47	8-32.8	8.5-22.5	2.5-18.8	1.75-17.3	23.5-34	22.8-32	23.8-35.3	0-17	2-15	0-8
	IQR	33.9-42.9	27.8-32.4	20.9-30.3	11.6-18.1	11.8-15.1	10.6-13.8	26.6-29.2	25.3-28.3	29.1-32	6-12.8	4-8	3-6
Delhi	Median	141	156	175	94.1	145	160	35.3	48.5	38.3	24	18	10
	Min-Max	25-161	90.5-202	74-210	14-122	87.8-226	83.5-270	20.8-44.3	28-69.7	20-76.3	0-37	0-35	0-18
	IQR	132-152	139-176	139-191	89.3-110	127-164	133-185	30.1-37.7	41.9-54.3	33.4-45.3	19-30.3	14-25	8-25
Khonkaen	Median	113	125	103	52.3	59.1	56.4	11	31.5	28.7	9	7	6
	Min-Max	45-244	48.8-142	49.5-142	21.3-76.5	24-74.5	26.3-80.8	3.5-16	26.5-37.8	18.5-40	0-16	4-12	0-11
	IQR	98.5-119	120-133	95.9-115	47.3-58.1	57.4-65.6	52.6-62	8.06-13.4	30.3-34.2	26.6-31.1	7-10.5	6-7	5-7
Langfang	Median	124	114	91.8	81.7	70.1	54.3	77.3	64.8	53.5	19	26	19
	Min-Max	43.5-173	28.8-155	54.3-146	53.7-160	33-140	33-100	53.7-160	33-140	33-100	0-40	13-51	0-38
	IQR	106-136	96.9-128	78.6-115	68.8-90.3	58.8-81.8	42.8-64.9	68.8-90.3	58.8-81.8	42.8-64.9	12.8-23	21-32.8	13-2
Madrid	Median	17.5	26.3	25	7.42	8.61	11	34	39.5	32.8	0	1	1
	Min-Max	9.5-40.5	15-35.8	8.25-39	2.5-17	4.75-15.8	4.25-28.3	25-43	29.5-47	26.8-37.7	0-13	0-5	0-3
	IQR	14.1-24.1	23.8-29.3	22.3-29.8	4.56-9.75	6.31-11	8-12.5	28-38.7	38-41.8	30.8-35.9	0-1	1-2	0.25
Newcastle	Median	28.8	48	24.5	11.8	17.4	10.9	27.5	29	28	18	14	13
	Min-Max	9.75-51	19.8-62.3	3.5-44.3	6.25-20	1.25-36.3	3-20.3	13.8-35.5	19.3-36.3	24-32	0-28	0-23	0-93
	IQR	25.5-38.8	37.8-53.9	19-29.8	9.56-14.19	12.1-22.3	8-13.5	19.8-30.2	24.6-31.8	26.8-29.9	9.5-20.8	9-17.8	10-11
Santiago	Median	70	71.3	67.8	61.9	59.4	59.2	26.5	24.5	33.5	21	29	37
	Min-Max	32-93.8	45-99.8	46.5-75	44-74	43-74	51-65.7	17.5-36.3	9.67-40.5	22.3-40.8	0-35	14-49	0-58
	IQR	63.5-79.6	68.6-80.2	61.8-70.3	56.9-67.3	54-63.6	57.1-62.2	22.8-30.2	21.8-26.2	29.1-37.2	18-23.8	23.3-33	27.3
Sao Paulo	Median	50.5	45.8	44.8	24.2	19.9	21.1	27	25	25.3	4	8	9
	Min-Max	30.8-71	25-63.5	0-53	14.5-32.5	10.3-28.5	13-50	17-36.8	13.8-34	16.8-38.5	0-41	0-21	0-22
	IQR	41.7-57.3	37.8-51.9	39.1-49.4	21.3-26.6	16.3-25.1	16.6-22.9	24.1-29.8	21.8-26.2	23.2-30.4	0-9	0-14	6-10
Silvri	Median	64.5	62	60	30.5	27	25.8	33.8	39.8	36.8	9	12	13
	Min-Max	37-83.5	27.3-89.8	6.75-76.5	18-41	13-40.8	11.5-35.8	23.3-48.3	30.5-52	29-44	0-25	4-23	0-28
	IQR	55.4-69.9	54.8-72.8	52.4-69.6	26.6-35.8	21.9-31.5	22-30.1	31.2-34.9	38.3-42.9	35.1-39.2	6-13.8	8-16	6.25
St Willington	Median	20.8	25	24.3	9.79	10	8.29	NR	NR	NR	NR	NR	NR
	Min-Max	10-33.3	16.3-40.8	6.75-33.3	4.75-14	5-13.5	3.25-12	NR	NR	NR	NR	NR	NR
	IQR	19.3-24.9	22.8-30.7	21.8-27.1	8.75-10.9	9-11.3	7.25-9.44	NR	NR	NR	NR	NR	NR
p value 2018-2019		0.7508			0.8294			0.6223			0.9214		
p value 2019-2020		0.4703			0.7508			0.7928			0.6932		
p value 2018-2020		0.8852			0.9264			0.3752			0.9474		

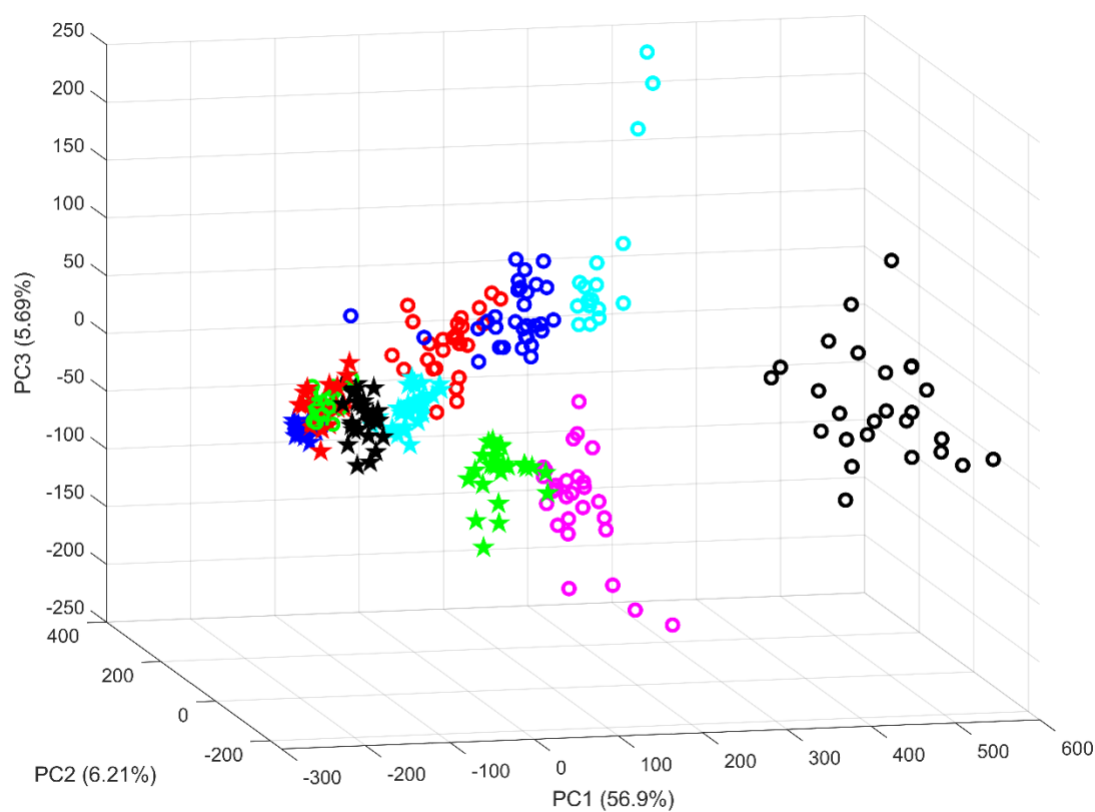
Correlation map (Fig. 11) displays no mismatches where no city gave a value of 0.95 against the other. It reveals that Bogota and Brescia are highly correlated. Similarly, Madrid, Newcastle, Sao Paulo and Silvri are correlated. Principal component analysis (PCA) was applied considering the data of the four parameters recorded at each city over the three years (2018-2020).



**Fig. 11** Correlation maps of the profile (considering the four parameters data over the three years) of (a) Bogota (1:31), (b) Brescia Villagio Sero (32:62), (c) California (63:92), (d) Delhi (94:124), (e) Khon Kaen (125:155), (f) Langfang (156:186), (g) Madrid (187:217), (h) Newcastle (218:248), (i) Santiago (249:279), (j) Sao Paulo (280:310) and (k) Silivri (311:341).

Only the first three principal components (PC1, PC2 and PC3) contributing to 68.8% of the overall data variations are presented in Figure 12. When the scores on the aforementioned three PCs were plotted, five distinct clusters were observed. Cities belong to same cluster have some common characteristics. The first cluster corresponds to Delhi, which has the highest

variance among the data. This could be a result of the fact that Delhi has the highest concentrations of particulate matters among cities under investigation due to dust from construction sites, wood-burning fires, exhaust from diesel generators, motor vehicle emissions, garbage open burning and illegal industrial activities [28].



**Fig. 12** PCA scores plot of the profile (considering the four parameters data over the three years) of (a) Bogota (blue circle), (b) Brescia Villagio Serono (red circle), (c) California (green circle), (d) Delhi (black circle), (e) Khon Kaen (cyan circle), (f) Langfang (magenta circle), (g) Madrid (blue star), (h) Newcastle (red star), (i) Santiago (green star), (j) Sao Paulo (black star) and (k) Silivri (cyan star).

The second cluster corresponds to Langfang, which is considered as heavily polluted city because of urbanization, industrialization, high population density [29, 30]. The loading plot (Online Resource 1) confirms these findings which shows that  $PM_{2.5}$  (1:24) and  $PM_{10}$  (25:48) are contributing to 56.9% of the variance among the data. The third cluster corresponds to Khon kaen where high levels of  $PM_{2.5}$  are reported in this region, of which biomass burning and transportation are two major sources [31]. The fourth cluster corresponds to Santiago which still ranks among the most polluted cities in the world. Annual average pollution levels exceed the WHO annual  $PM_{10}$  limits on all the city's monitoring stations [32]. The last two clusters were adjacent where cluster five corresponds to Bogota, and Brescia. The cities of this cluster are densely populated, heavily industrialized and highly polluted [33]. Finally, cluster 6 represents Madrid, Newcastle, Sao Paulo and Silivri. Vehicular emissions are the main source of air pollution in these cities [34, 35].

#### 4- Conclusion

The emission of environmental pollutants varies significantly across different cities, primarily due to differences in transportation systems, industrial structures, and population densities. The COVID-19 pandemic has had detrimental effects on both public health and the economy. However, the implementation of lockdown measures and the subsequent decrease in industrial activities have resulted in a notable reduction in air pollution levels. Detailed analysis of data reveals a distinct decline in the concentrations of major air pollutants such as  $PM_{2.5}$ ,  $PM_{10}$ , and  $NO_2$ . The environment has demonstrated its capacity for recovery during the period of lockdown, showcasing the potential for reducing pollution levels on a broader scale. This temporary improvement in environmental pollution should serve as a motivating factor for governments and individuals to actively pursue long-term strategies for pollution reduction. By learning from the success observed during the lockdown, it becomes imperative to explore sustainable practices and policies that can ensure a continued reduction in pollution levels while safeguarding public health.

The application of Principal Component Analysis (PCA) and correlation mapping has facilitated the establishment of connections between different pollutants, enabling the organization of monitoring stations within cities based on the significance of these variables. These findings are instrumental in formulating and evaluating effective policies aimed at addressing environmental pollution while simultaneously protecting public health.

On a global scale, the minimization of air pollution is of utmost importance in making progress towards the 2030 Agenda for Sustainable Development, particularly Sustainable Development Goals 3 (Good Health and Well-Being), 7 (Affordable and Clean Energy), and 11 (Sustainable Cities and Communities). By prioritizing pollution reduction efforts, societies can strive towards achieving these goals, fostering a healthier and more sustainable future for all.

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### Declarations

### Competing interests

The authors declare no conflict of interest.

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### Data Availability Statement

The datasets generated during and/or analysed during the current study are available from: India Meteorological Department (IMD) – India Central Pollution Control Board (CPCB), UK-AIR, air quality information resource - Defra / UK, Turkey National Air Quality Monitoring Network, Regional Agency for the Protection of the Environment of Lombardy / Italy and Air Resources Board (CARB) - Air Now - US EPA, CETESB-Environmental Company of the State of Sao Paulo, Hebei Province Environment Protection Agency, National Air Quality System in Chile, The Environmental Observatory of Bogotá, Air Quality in Madrid, Atmosphere Protection

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### Ethical approval

Not required

### References

- [1] C. Indranil, P. Maity. "COVID-19 outbreak: Migration, effects on society, global environment and prevention" *Science of the total environment* 728, p. 138882, 2020.
- [2] H. Chaolin, Y. Wang, X. Li, L. Ren, J. Zhao, Y. Hu, L. Zhang et al., "Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China," *The lancet*, 395(10223), pp. 497-506, 2020.
- [3] M. J. Jaime, R. M. Carrillo-Larco, C. Ferreccio, I. R. Hambleton, P. A. Lotufo, R. Nieto-Martínez, B. Zhou et al. "Trends in cardiometabolic risk factors in the Americas between 1980 and 2014: a pooled analysis of population-based surveys," *The Lancet Global Health*, 8(1), pp.123-133, 2020.
- [4] Eurosurveillance Editorial Team. "Note from the editors: World Health Organization declares novel coronavirus (2019-nCoV) sixth public health emergency of international concern." *Eurosurveillance* 25(5), 200131e, 2020.
- [5] World Health Organization (WHO), 2020b. Clinical Management of Severe Acute Respiratory Infection When Novel Coronavirus (2019-nCoV) Infection Is Suspected: Interim Guidance.
- [6] OECD, 2020, "Flattening the COVID-19 peak: Containment and mitigation policies", OECD Policy Responses to Coronavirus (COVID-19), OECD Publishing, Paris, <http://www.oecd.org/coronavirus/policy-responses/flattening-the-covid-19-peak-containment-and-mitigation-policies-e96a4226>
- [7] C. Indranil, P. Maity. "COVID-19 outbreak: Migration, effects on society, global environment and prevention," *Science of the total environment*, 728, p. 138882, 2020.
- [8] World Health Organization (WHO), 2020a. World Health Organization. Novel coronavirus (2019-nCoV). <https://www.who.int/emergencies/diseases/novel-coronavirus-2019> (accessed July 07 2020).
- [9] W. Annelies, D. O. Freedman, "Isolation, quarantine, social distancing and community containment: pivotal role for old-style public health measures in the novel coronavirus (2019-nCoV)

outbreak," *Journal of travel medicine*, 27(2), taaa020, 2020.

[10] U. Nevin, R. M. Schapira, "Effects of ozone on lung function and lung diseases," *Current opinion in pulmonary medicine*, 9(2), pp. 144-150, 2003.

[11] B. Michael, "How much, how long, what, and where: air pollution exposure assessment for epidemiologic studies of respiratory disease." *Proceedings of the American Thoracic Society* 7(2), pp.111-115, 2010.

[12] J. Chauhan, M. T. Krishna, A. J. Frew, S. T. Holgate, "Exposure to nitrogen dioxide (NO<sub>2</sub>) and respiratory disease risk", *Reviews on environmental health*, 13(1-2), pp.73-90, 1998.

[13] R. Subodh, B. N. Gupta, T. Husain, H. Chandra, N. Mathur, B. S. Pangtey, S. V. Chandra, N. Garg, "A cross-sectional study of pulmonary function among workers exposed to multimetals in the glass bangle industry," *American journal of industrial medicine*, 20(3), pp.391-399, 1991.

[14] T. Ira, J. Balmes, F. Lurmann, L. Ngo, S. Alcorn, N. Künzli, "Chronic exposure to ambient ozone and lung function in young adults," *Epidemiology*, 16(6), pp. 751-759, 2005.

[15] C. Aaron J., M. Brauer, R. Burnett, H. R. Anderson, J. Frostad, K. Estep, K. Balakrishnan et al., "Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015," *The lancet*, 389(10082), pp. 1907-1918, 2017.

[16] World Health Organization (WHO), 2017. Evolution of WHO Air Quality Guidelines: Past, Present and Future. <http://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2017/evolution-of-who-air-quality-guidelines-past,-present-and-future-2017> (accessed 14 April 2020).

[17] World Health Organization (WHO) Regional Office for Europe, 2013. Review of evidence on health aspects of air pollution – REVIHAAP project: final technical report. Copenhagen: WHO Regional Office for Europe (<https://www.euro.who.int/en/health-topics/environment-and-health/air-quality/publications/2013/health-risks-of-air-pollution-in-europe-hrapie-project.-recommendations-for-concentration-response-functions-for-cost-benefit-analysis-of-particulate-matter,-ozone-and-nitrogen-dioxide>, accessed 18 May 2020).

[18] G. Sneha, "The influence of COVID-19 on air quality in India: a boon or inutile," *Bulletin of environmental contamination and toxicology*, 104, pp. 724-726, 2020.

[19] C. Matteo, J. T. Davis, M. Ajelli, C. Gioannini, M. Litvinova, S. Merler, A. P. Piontti et al. "The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak," *Science*, 368(6489), pp.395-400, 2020.

[20] C. Simiao, D. E. Bloom, "The macroeconomic burden of noncommunicable diseases associated with air pollution in China," *PloS one*, 14(4) (2019), e0215663, 2019.

[21] N. Chen, M. Zhou, X. Dong, J. Qu, F. Gong, Y. Han, Y. Qiu et al, "Epidemiological and clinical characteristics of 99 cases of 2019 novel coronavirus pneumonia in Wuhan, China: a descriptive study," *The lancet*, 395(10223), 507-513, 2020.

[22] IEA, 2019, Multiple Benefits of Energy Efficiency, IEA, Paris <https://www.iea.org/reports/multiple-benefits-of-energy-efficiency>.

[23] IEA, 2020a, Monthly electricity statistics, IEA, Paris <https://www.iea.org/reports/monthly-electricity-statistics>.

[24] IEA, 2020b, Global Energy Review 2020, IEA, Paris <https://www.iea.org/reports/global-energy-review-2020>.

[25] INE, 2020, <https://www.ine.es/dyngs/INEbase/en/operacion.htm?c=EstadisticaC&cid=1254736176906&menu=ultiDatos&idp=1254735576820>

[26] IEA, 2020c, Changes in transport behaviour during the Covid-19 crisis, IEA, Paris <https://www.iea.org/articles/changes-in-transport-behaviour-during-the-covid-19-crisis>.

[27] E. Miguel, A. Segers, R. Kranenburg, X. Querol, A. Alastuey, R. Borge, D. De la Paz, G. Gangoiti, M. Schaap, "Analysis of summer O<sub>3</sub> in the Madrid air basin with the LOTOS-EUROS chemical transport model," *Atmospheric Chemistry and Physics*, 19(22), pp. 14211-14232, 2019.

[28] C. Jayajit, P. Basu, "Air quality and environmental injustice in India: Connecting particulate pollution to social disadvantages." *International Journal of Environmental Research and Public Health* 18(1), p. 304, 2021.

[29] H. Chaolin, Y. Wang, X. Li, L. Ren, J. Zhao, Y. Hu, L. Zhang et al, "Clinical features of patients

infected with 2019 novel coronavirus in Wuhan, China," *The lancet*, 395(10223), pp. 497-506, 2020.

[30] W. Dongdong, B. Jiang, F. Li, and W. Lin, "Investigation of the air pollution event in Beijing-Tianjin-Hebei region in December 2016 using WRF-chem," *Advances in Meteorology*, 2018.

[31] N. Daiju, N. Thi Kim Oanh, K. Sato, M. Huo, D. A. Permadi, N. N. Ha Chi, T. Ratanajaratroj, I. Pawarmart, "Pollution characteristics and policy actions on fine particulate matter in a growing Asian economy: The case of Bangkok Metropolitan Region," *Atmosphere*, 10(5), p. 227, 2019.

[32] M. Guillermo, "Too polluted to work? The gendered correlates of air pollution on hours worked," *IZA Journal of Labor Economics*, 7(1), p. 7, 2018.

[33] European Environmental Agency (EEA), 2019, URL <https://www.eea.europa.eu/publications/air-quality-in-europe-2019>.

[34] F. Rosa, H. Özdemir, B. O. Akkoyunlu, A. Ünal, M. Tayanç, "Seasonal variation of carbonaceous PM<sub>2.5</sub> in an Istanbul traffic site," *Atmospheric Pollution Research*, 11(12), pp. 2110-2118, 2020.

[35] B. Rafael, J. Lumbreras, J. Pérez, D. de la Paz, M. Vedrenne, J. M. de Andrés, M. E. Rodríguez, "Emission inventories and modeling requirements for the development of air quality plans. Application to Madrid (Spain)." *Science of the Total Environment* 466, pp. 809-819, 2014.