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Abbas, I, Khan, I, Ginige, T and Abdelkader, A (2023) Air Quality Transformation in Twelve Major Cities during Covid-19 Lockdowns: A Global Assessment. International Journal of Data Science and Advanced Analytics, 5 (5). pp. 264-271. ISSN 2563-4429

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

Ismail I. Abbas[1*], Iftikhar Khan[2], Tilak A. Ginige[3] and Amor Abdelkader[4]

[1]Laboratory of Analysis of Organic Compounds (LACO), Chemistry and Biochemistry Department, Faculty of Sciences, Section I, Lebanese University, Hadath, Lebanon. E-mail: ismail.abbas@ul.edu.lb; ismailabbas057@gmail.com; Tel= +961.3.601140.
[2] Faculty of Science, School of Pharmacy and Biomolecular Sciences, Liverpool John Moores University, Liverpool, L3 5UX, UK. E-mails: I.Khan@ljmu.ac.uk.
[3] Department of Life & Environmental Science, Faculty of Science and Technology, Bournemouth University, Poole, Dorset BH12 5BB, UK. E-mail: tginige@bournemouth.ac.uk.
[4] Department of Design and Engineering, Faculty of Science & Technology, Bournemouth University, Poole, Dorset BH12 5BB, UK. E-mail: aabdelkader@bournemouth.ac.uk.
* Corresponding Author

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_2), ozone (O_3), and particulate matter (PM10 and $PM_{2.5}$) 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_2, O_3, $PM_{2.5}$, and PM10 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**

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 (PM2.5), Particulate Matter 10 (PM_{10}), Ozone (O_3), Nitrogen dioxide (NO_2) and Sulfur dioxide (SO_2) 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 µm and less than 10 µm, 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 µm 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 µg/m3 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 NO2). 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_2, $PM_{2.5}$, PM_{10} and O_3 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_2, $PM_{2.5}$, PM_{10} and O_3) 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^2)**	**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	22,000000	Monsoon-influenced humid subtropical	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].

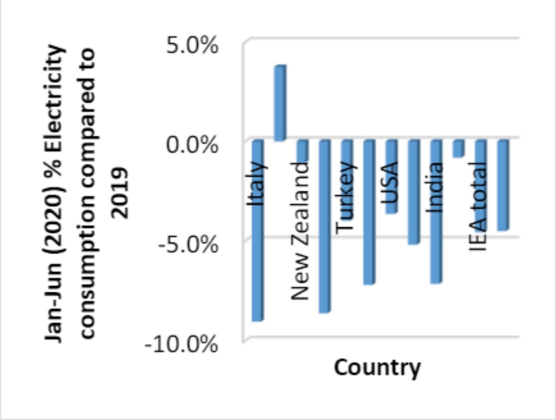

Fig. 1 Electricity consumption during the first six months of 2020 as compared to 2019.

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].

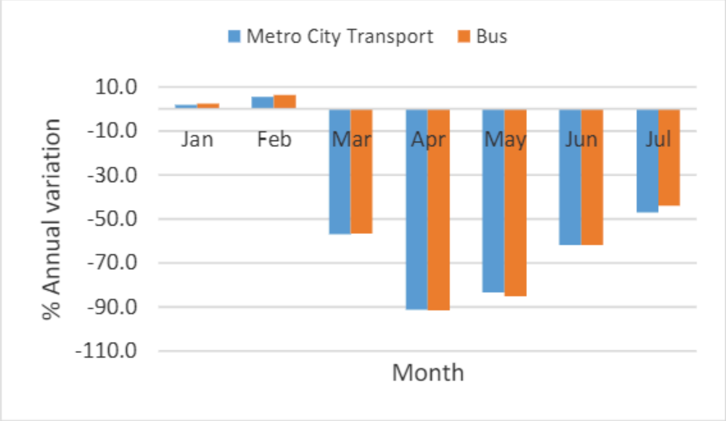

Fig. 2 Annual variation in metro and bus transportation in Madrid/Spain in 2020 as compared to 2019.

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 ($PM_{2.5}$, PM_{10}, NO_2, and O_3) 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.

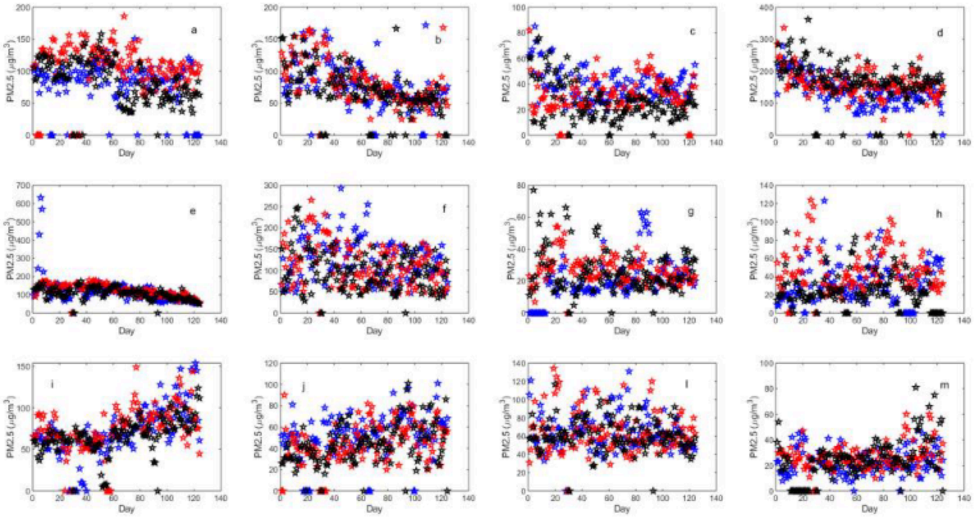

Fig. 3 Daily change of PM2.5 between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM2.5 for (a) Bogota, (b) Brescia Villagio Serono, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i)Santiago, (j) Sao Paulo, (k) Silvri and (l) St Willington.

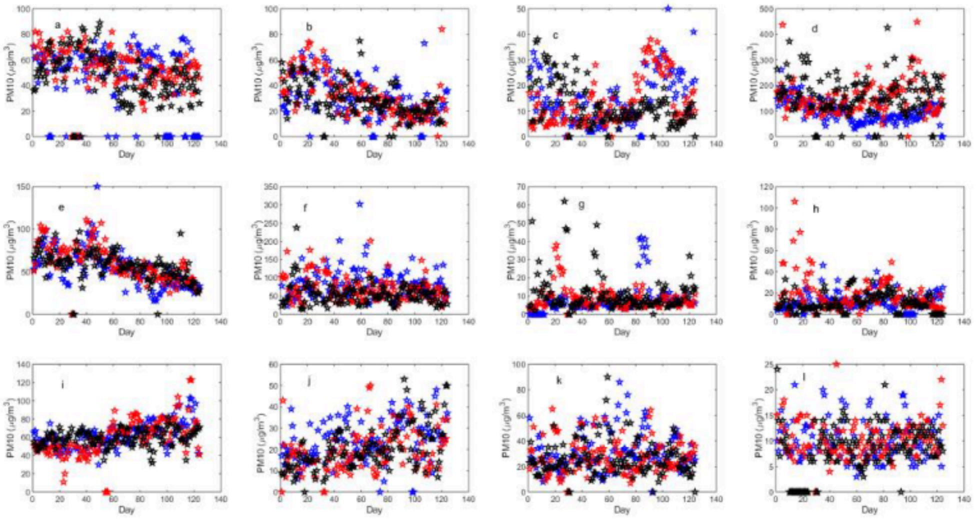

Fig. 4 Daily change of PM_{10} between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM2.5 for (a) Bogota, (b) Brescia Villagio Serono, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i)Santiago, (j) Sao Paulo, (k) Silvri and (l) St Willington.

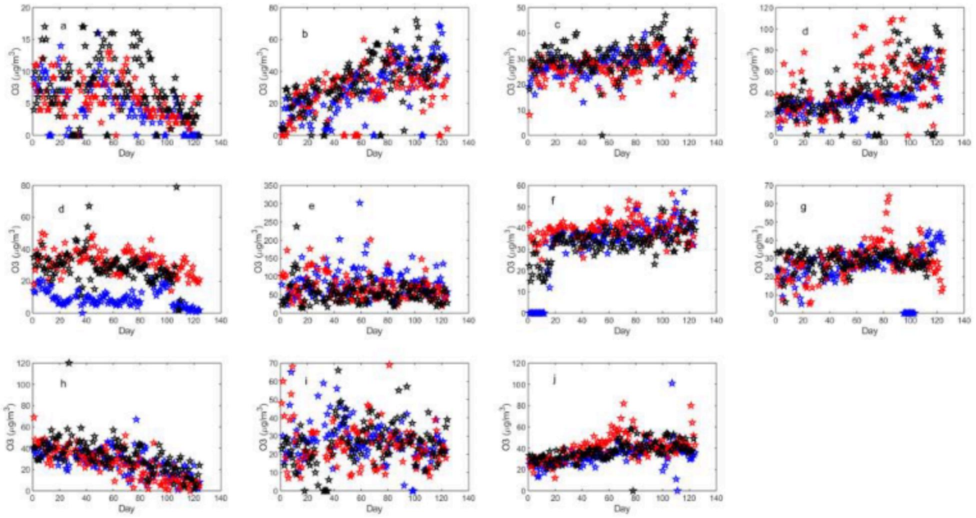

Fig. 5 Daily change of O3 between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM2.5 for (a) Bogota, (b) Brescia Villagio Serono, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i)Santiago, (j) Sao Paulo and (k) Silvri.

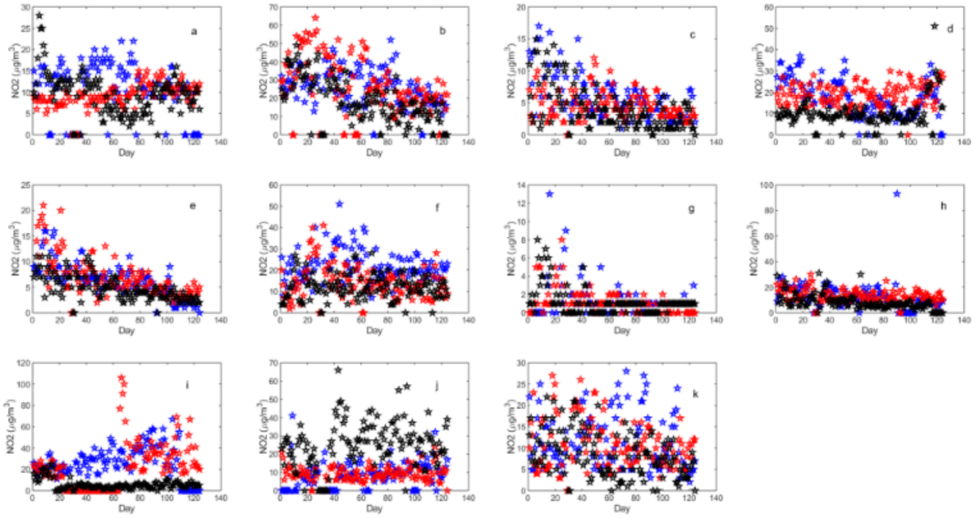

Fig. 6 Daily change of NO_2 between March and May 2018 (blue), 2019 (red) and 2020 (black) for PM2.5 for (a) Bogota, (b) Brescia Villagio Serono, (c) California, (d) Delhi, (e) Khonkaen, (f) Langfang, (g) Madrid, (h) Newcastle, (i)Santiago, (j) Sao Paulo and (k) Silvri.

Figure 7 illustrates the changes in $PM_{2.5}$ concentrations before and during the lockdown in eleven cities. Almost all cities demonstrated a reduction in $PM_{2.5}$ concentrations during the lockdown, with significant decreases observed in Delhi, Newcastle, and California. According to the World Health Organization [16], the standard limit for PM2.5 is 25 µg/m^3. Prior to the lockdown, the monthly average $PM_{2.5}$ concentration in all cities exceeded this limit. However, during the lockdown, $PM_{2.5}$ 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 $PM_{2.5}$, with a decrease of 59.7% during February 2020 compared to 2019 ($[PM_{2.5}]_{Before}$ = 59.56 µg/m^3; $[PM_{2.5}]_{During\ lockdown}$ = 24.0 µg/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 Silivri, respectively.

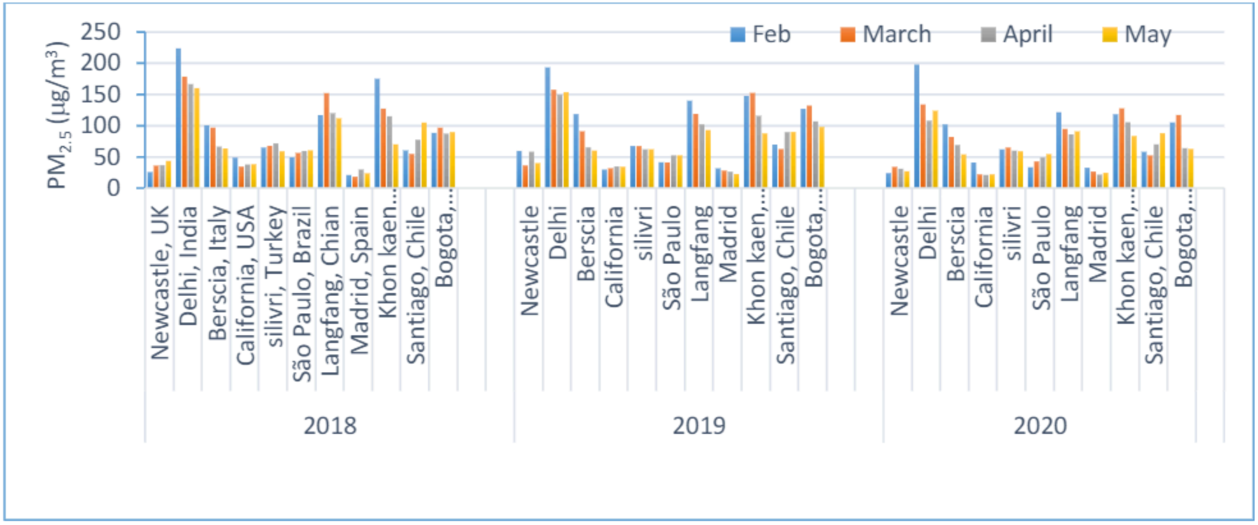

Fig. 7 Variations of $PM_{2.5}$ concentrations during 2018, 2019 and 2020 for February-May in Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

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.

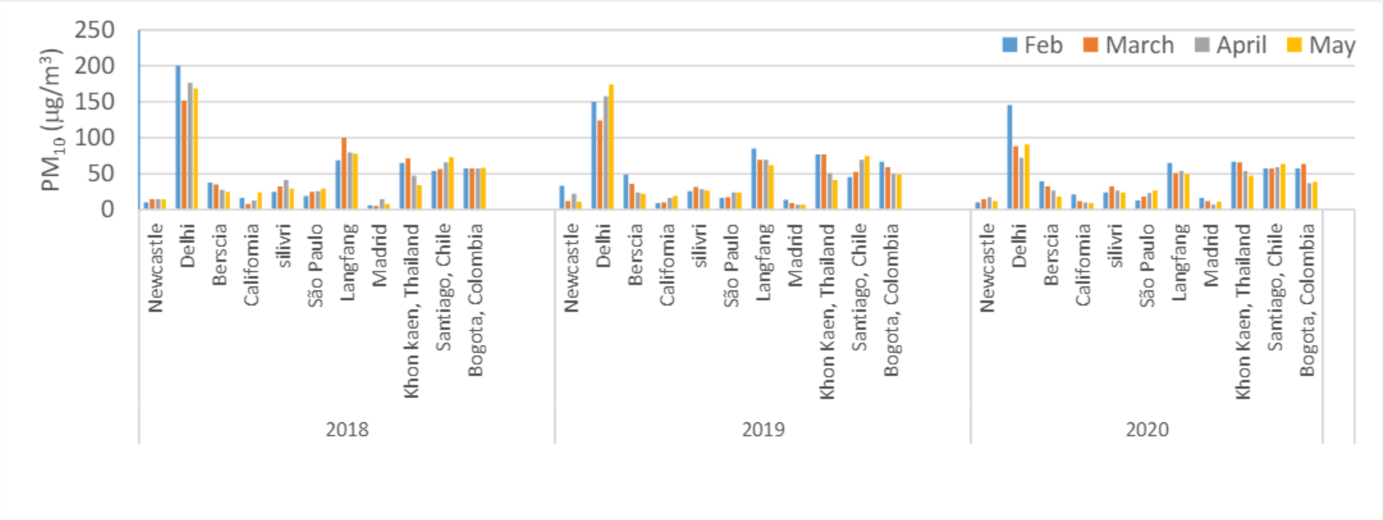

Fig. 8 Variations of PM_{10} concentrations during 2018, 2019 and 2020 for February-May Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

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.

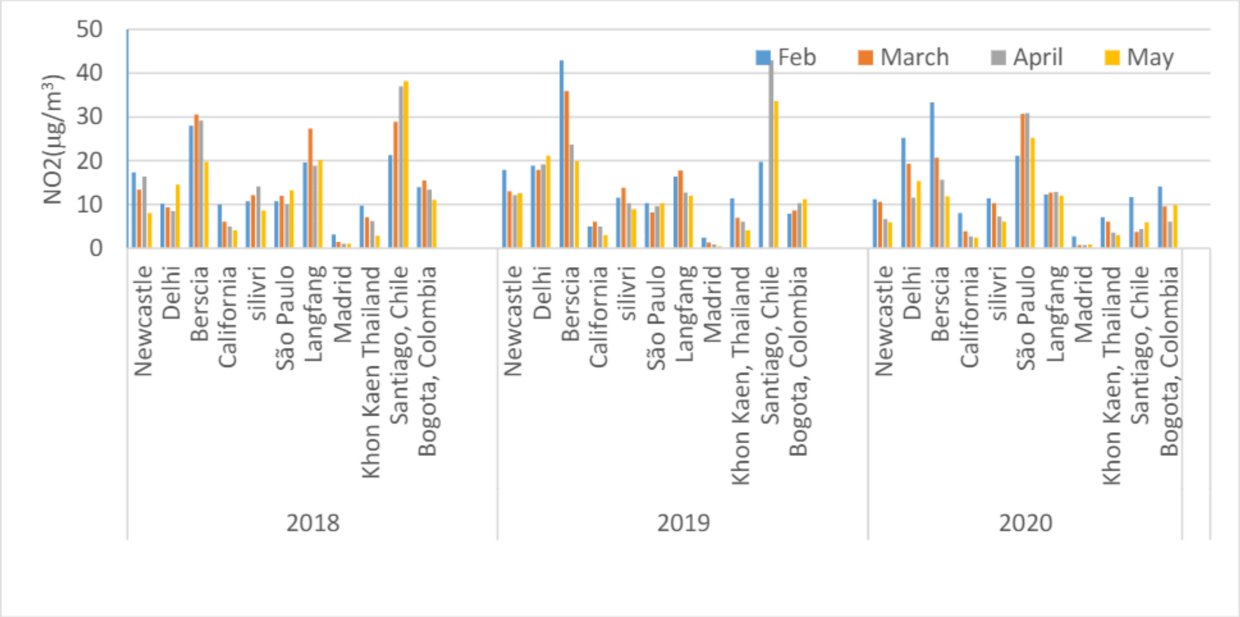

Fig. 9 Variations of NO_2 concentrations during 2018, 2019 and 2020 for February-May in Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

Regarding 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 NO_2 levels (Fig. 10). The increase in O_3 levels in these cities may be attributed to photochemical reactions involving ozone precursors (NO_x) under favorable weather conditions for O_3 production [27]. As O_3 gas is not directly emitted into the atmosphere but formed through the presence of NO_x, volatile organic compounds (VOCs), and solar radiation, there are complex factors beyond emissions alone that influence O_3 concentrations. Therefore, the influence of meteorology on the variation of O_3 concentrations should also be examined.

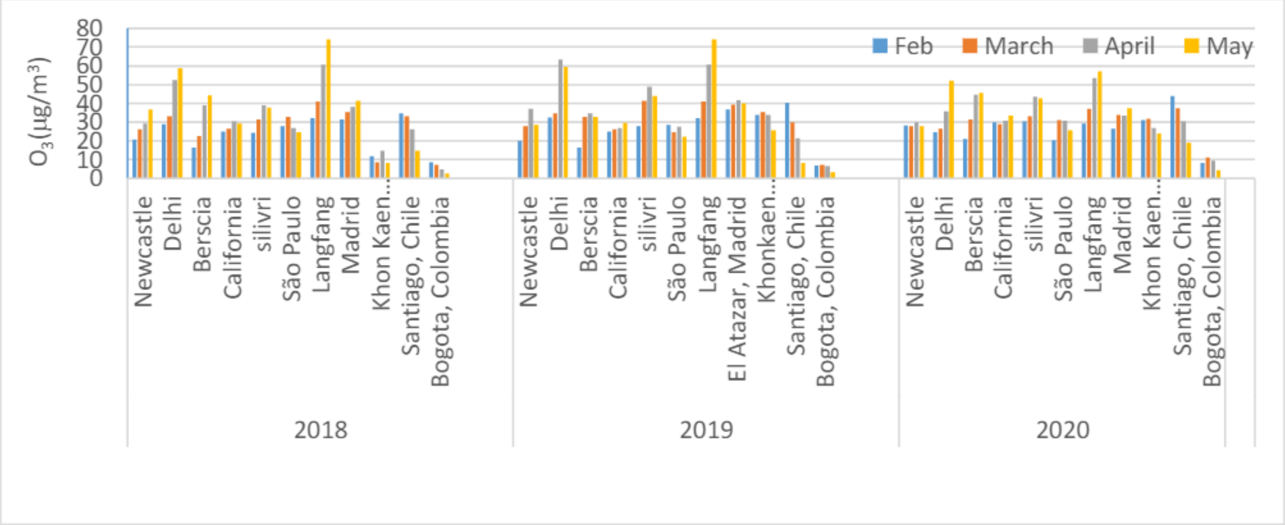

Fig. 10 Variations of O_3 concentrations during 2018, 2019 and 2020 for February-May in Bogota, Brescia, California, Delhi, Khon Kaen, Langfang, Madrid, Newcastle, Santiago, Sao Paulo and Silivri.

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 $PM_{2.5}$ is 0.0 µg/m3at Sao Paulo in 2020 and the lowest concentrations recorded for each of PM_{10}, O_3 and NO_2 are 0.0 µg/m^3 at Bogota in 2018. On the other hand, the highest concentrations obtained for $PM_{2.5}$, PM_{10}, O_3 and NO_2 are 244 at Khon Kaen in 2018, 160 µg/m^3 at Delhi in 2020, 140 at Langfang in 2018 and 93 µg/m^3 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^3 for $PM_{2.5}$, PM_{10} and NO_2 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 Villaggio Sereno	**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	10-1
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						
	IQR	19.3-24.9	22.8-30.7	21.8-27.1	8.75-10.9	9-11.3	7.25-9.44						
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 Silivri 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).

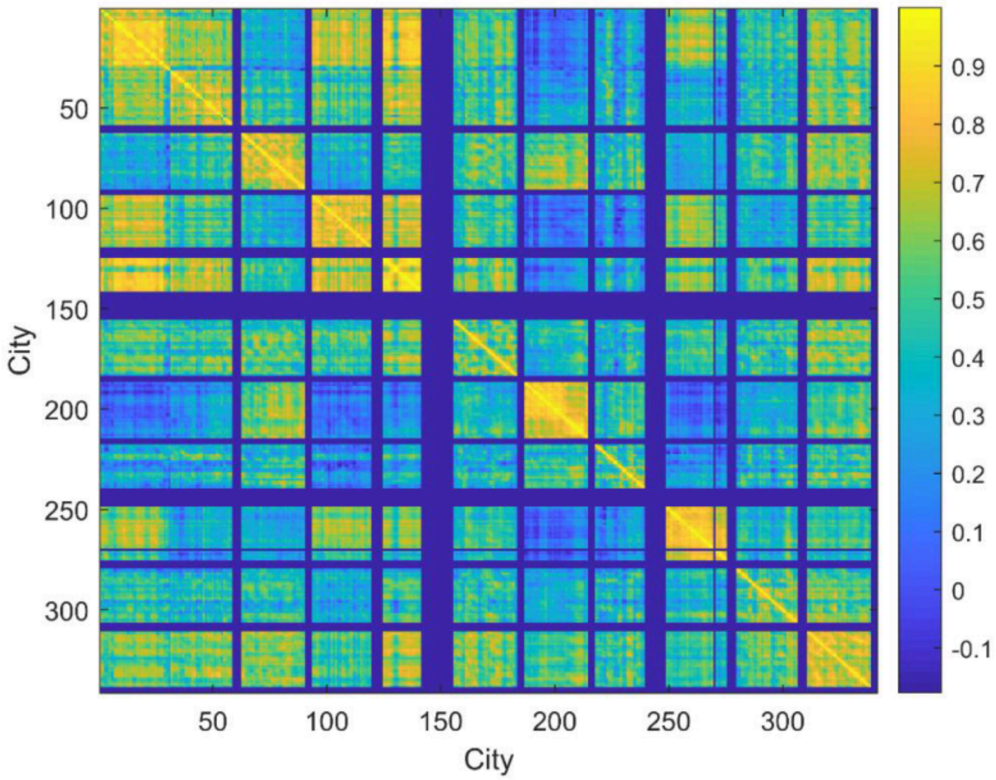

Fig. 11 Correlation maps of the profile (considering the four parameters data over the three years) of (a) Bogota (1:31), (b) Brescia Villagio Serono (32:62), (c) California (63:92), (d) Delhi (94:124), (e) Khon Kaen (125:155), (f) Langfang (156:186), (g) Madrid (187:217), (h) Newcastle (218:248), (i)Santiago (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].

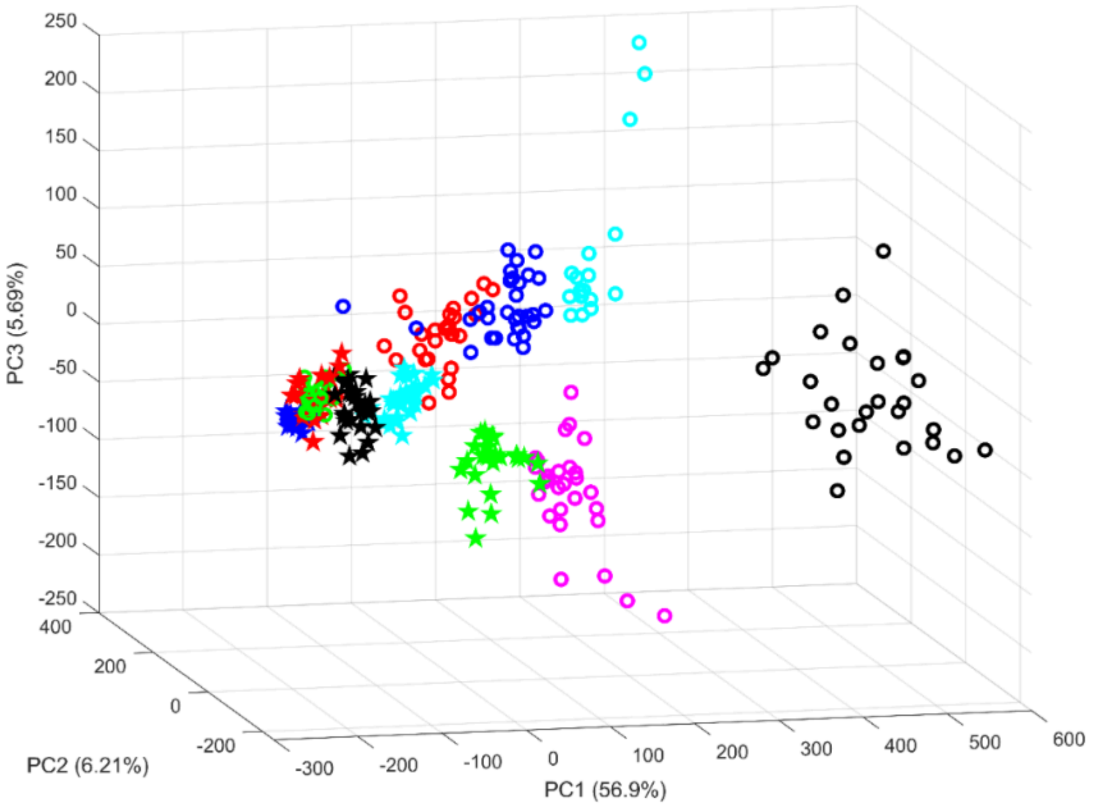

Fig. 12 PCA scores plot of the profile (considering the four parameters data over the three years) of (a) Bogota (blue circle), (b) Brescia Villagio Serono (red circle), (c) California (green circle), (d) Delhi (black circle), (e) Khon Kaen (cyan circle), (f) Langfang (magenta circle), (g) Madrid (blue 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 PM10 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.

Acknowledgements

The authors are thankful to local and regional agencies in charge of air monitoring stations in USA, UK, India, Turkey, Thailand, Brazil, Colombia, Chile, Spain, China and Italy.

Declarations

Competing interests

The authors declare no conflict of interest.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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 Service - European Environment Agency, Division of Air Quality Data, Air Quality and Noise Management Bureau, Pollution Control Department / Thailand.

Ethical approval

Not required

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