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Impacts of partial to complete COVID-19 lockdown on NO_2 and $PM_{2.5}$ levels in major urban cities of Europe and USA

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ABSTRACT

SARS CoV-2 (COVID-19) coronavirus has been causing enormous suffering, death, and economic losses worldwide. There are rigorous containment measures on industries, non-essential business, transportation, and citizen mobility to check the spread. The lockdowns may have an advantageous impact on reducing the atmospheric pollutants. This study has analyzed the change in atmospheric pollutants, based on the Sentinel–5Ps and ground-station observed data during partial to complete lockdown period in 2020. Results revealed that the mean tropospheric NO_2 concentration substantially dropped in 2020 due to lockdown against the same period in 2019 by 18–40% over the major urban areas located in Europe (i.e. Madrid, Milan, Paris) and the USA (i.e. New York, Boston, and Springfield). Conversely, urban areas with partial to no lockdown measures (i.e. Warsaw, Pierre, Bismarck, and Lincoln) exhibited a relatively lower dropdown in mean NO_2 concentration (3 to 7.5%). The role of meteorological variability was found to be negligible. Nevertheless, the reduced levels of atmospheric pollutants were primarily attributed to the shutdown of vehicles, power plants, and industrial emissions. Improvement in air quality during COVID-19 may be temporary, but regulatory bodies should learn to reduce air pollution on a long-term basis concerning the trade-offs between the environment, society, and economic growth. The intersection of urban design, health, and environment should be addressed by policy-makers to protect public health and sustainable urban policies could be adopted to build urban resilience against any future emergencies.

1. Introduction

The severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2) is widely known as COVID-19, and its outbreak started from Wuhan, Hubei Province, China in late December 2019 (Lai et al., 2020; Lu et al., 2020). It has been rapidly spreading across the world and affected over 215 countries (Wang et al., 2020; Laxminarayan et al., 2020), with more than 34.5 million COVID-19 cases and 1.02 million deaths globally as of 2nd October 2020 (JHU, 2020). Epidemiological investigations reported that the pneumonia-like cases were originated in Wuhan and linked to the seafood, wild animal market, and known to be of zoonotic origin. As per the World Health Organization (WHO) and other latest studies, this virus transmits from human to human by direct contact in the form of tiny respiratory droplets (Carlos et al., 2020; Li et al., 2020; Wang et al., 2020). Global travel is one of the primary reasons for its worldwide spread (Munster et al., 2020). The WHO declared COVID-19 as the latest Public Health Emergency of International Concern (PHEIC) on 30th January 2020, which follows H1N1 in 2009, Polio in 2014, Ebola in West Africa in 2014, Zika in 2016, and Ebola in the Democratic Republic of Congo in 2019. The COVID-19 pandemic has forced governments to declare 'lockdowns' in over 100 countries worldwide. As a result, economic activity has come to a standstill situation in many countries due to restrictions on industrial production, power plants, non-essential business, transport systems, institutes, offices, travel bans, and citizen mobility. Lockdown dates differed between countries but were mostly implemented in March 2020 except in Hubei, China (Table 1). The easing of containment measures mainly initiated from the 2nd week of May 2020 (Table 1).

Nitrogen dioxide (NO_2) is a key air pollutant that is emitted from both natural processes (e.g. lighting) and anthropogenic activities, such

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Table 1
Country-wise lockdown dates and respective COVID-19 cases and deaths as of 2nd October 2020 (JHU, 2020).

Country/ city	Lockdown dates in 2020	Easing Lockdown dates in 2020	COVID-19 Cases	COVID-19 deaths
France	17-March	11-May	629,134	32,170
Italy	09-March	03-May	319,908	35,941
Spain	14-March	09-May	789,932	32,086
Sweden	No-lockdown	–	94,283	5895
Poland	13-March	11-April	95,773	2570
USA	22-March	13-June	7,318,110	208,485

as fossil fuel combustion, industrial production, vehicular emissions (Beirle et al., 2003). Globally, about 50 Tg of nitrogen oxides (NO_x) is released to atmosphere annually; out of total, about 23% is originated from natural sources, 58% is from burning of fossil fuel (traffic, power plants, industry, etc.), and the remaining 19% is released from biomass burning (Dentener et al., 2006). Over the last few decades, the rapid increase in urbanization, industrial activity and transport emissions has resulted in increased emissions of NO_2 and a reduction in air quality (Sun et al., 2018; Zheng et al., 2019). Recent research reported that NO_x emission has caused ~107,626 premature deaths globally in 2015 (Anenberg et al., 2017), resulted in 4 million asthma cases annually (Achakulwisut et al., 2019), caused increased cardiovascular and respiratory mortality rates (Chen et al., 2012) and exacerbated pre-existing respiratory infections (Chauhan et al., 2003).

Particulate matter (PM) less than 2.5 μm (termed $PM_{2.5}$) is another major air pollutant. It is generally produced through the combustion of fossil fuels and organic matter and due to natural activity such as volcanic eruption and dust emissions. According to (Cohen et al., 2017), the global mean concentration of $PM_{2.5}$ has increased by 11.2% from 39.7 (1990) to 44.2 $\mu g\ m^{-3}$ (2015) with the poorest air quality in the world's ten most populous countries, whilst relatively low concentration in the USA, Brazil, Russia, and Japan and lowest in European countries such as Sweden, Finland, and Iceland (Cohen et al., 2017). Anthropogenic emissions from residential, industrial, and transport sectors are dominant source of $PM_{2.5}$ emission in many countries in Asia, and the magnitude of which has been steadily increasing over time (Crippa et al., 2018). Fine particulate matter is most detrimental to human health and can lead to respiratory problems, cardiovascular disease, and lung cancer (Xing et al., 2016). Globally, outdoor air pollution has led to ~4.2 million premature deaths annually in 2016 (WHO, 2016). In addition to increased mortality, every 10 $\mu g\ m^{-3}$ increase in $PM_{2.5}$ concentration increases the probability of lung cancer by 36% (Raaschou-Nielsen et al., 2013).

The rigorous containment measures in lockdowns during the SARS COVID-19 pandemic resulted in a decline in transport and industrial activities. These strict government measures caused a significant drop down in atmospheric pollutants, namely CO_2, CO, SO_2, NO_2, and PM concentration and aerosols levels in the major industrial countries (Kanniah et al., 2020; Le Quéré et al., 2020; Sharma et al., 2020). For instance, global CO_2 emissions from fossil fuel use and cement production have decreased by 5.8% during Jan–March 2020 compared to 2019 levels with largest decreases in emissions from industry, followed by road transportation, power generation, residential, maritime transport, and aviation (Liu et al., 2020). At the regional scale, the largest decreases in CO_2 emissions occurred in China, followed by Europe (EU-27 and UK) and the USA (Liu et al., 2020). It was reported that global anthropogenic CO_2 emissions reduced by 7% in March 2020 against the same time in 2019 due to global lockdown (Safarian et al., 2020). The coal-based CO_2 emissions reduced by 17% (11 to 25%) in early April 2020 compared to the average condition of 2017–19 for the same period (Le Quéré et al., 2020). Consequently, (Yusup et al., 2020) reported atmospheric CO_2 concentration reduced moderately by 1.8% during the lockdown in first quarter of 2020 compared to 2017–18 based on a ground monitoring station data from Peninsula Malaysia. However, it was plummeted substantially by 18–39% in India during the lockdown in April 2020 (Parida et al., 2020). In contrast, the drop in CO_2 concentration was found to be insignificant at Mauna Loa Observatory (MLO) at Hawaii Island due to high average residence time of CO_2 in the atmosphere.

Several studies have revealed large reductions of up to 20–40% in NO_2 concentration in cities in China, India, Malaysia, Europe, South America, and the USA in 2020 (Abdullah et al., 2020; Acharya et al., 2021; Dutheil et al., 2020; Le et al., 2020; Lolli et al., 2020; Muhammad et al., 2020; Patel, 2020; Shrestha et al., 2020; Tobías et al., 2020; Wang, & Su, 2020; Zhang et al., 2020). In central China, NO_2 and $PM_{2.5}$ concentrations decreased by 61% and 30%, respectively (Xu et al., 2020). In Eastern China, NO_2 concentrations reduced by 30%, which was relatively lower than that of central China, possibly related to the lower usage of coal and oil (Filonchyk et al., 2020). In northern China, NO_2 and $PM_{2.5}$ concentrations decreased by 24.7% and 5.9%, respectively (Bao & Zhang, 2020). Nearly 336 cities across China showed NO_2 and $PM_{2.5}$ concentrations decreased by 16% and 14%, respectively (Chen et al., 2020). In India, NO_2 and $PM_{2.5}$ concentrations were decreased by 18–53% and 35–39%, respectively from several cities of India (Chauhan & Singh, 2020; Mahato et al., 2020; Parida et al., 2021). The highest decrease in NO_2 concentration was found in Bangalore (87%) whilst $PM_{2.5}$ concentration in Ahmedabad (68%) among 18 cities in India (Navinya et al., 2020). In Barcelona, Spain, NO_2 and PM_{10} levels were decreased by 51% and 45%, respectively (Tobías et al., 2020). The European Environment Agency (EEA) has reported about 47% and 55% drop in NO_2 concentrations from the cities of Bergamo (Italy) and Barcelona (Spain), respectively (EEA, 2020a). In Naples (Italy), NO_2 and PM_{10} concentrations dropped to 45–50% and 29–49%, respectively during the lockdown period (Sannino et al., 2020). Similarly in Rio de Janeiro and São Paulo (Brazil), NO_2 and PM_{10} levels decreased by 42% and 15% respectively during lockdowns associated with the closedown of anthropogenic emissions (Dantas et al., 2020; Siciliano et al., 2020). In the capital city of Quito in Ecuador (South America), significant reductions of NO_2 (68%) and $PM_{2.5}$ (29%) concentrations were measured at all the monitoring sites (Zalakeviciute et al., 2020). The NO_2 levels were reduced by 18–38% in urban areas of Europe and 19–28% in urban areas of North America (Bauwens et al., 2020). A number of studies reported changes in NO_2 concentration by 30% in the urban northeastern USA (Blumberg, 2020) with the largest reduction in urban counties compared to the rural counties (Berman & Ebisu, 2020). The percent decreases of $PM_{2.5}$ was not as large as compared to NO_2 concentration during COVID-19, possibly it could be contributed by multiple non-transportation sources, such as food industries and biomass burning. Over the central valley and southern California, it was reported that the NO_2 concentration was decreased by 40% in Los Angeles, 38% in Fresno, and 20% in Bakersfield and San Francisco because of COVID-19 lockdown (Naeger & Murphy, 2020). After accounting for the effects of meteorological conditions, lockdowns have found responsible for reduction of NO_2 and $PM_{2.5}$ levels by about 60% and 31% in 34 countries using more than 10,000 air quality stations data that attributed to reductions in vehicle transportation (Venter et al., 2020). By analyzing about 30 countries in Europe, it was also reported that lockdown has resulted in a decline in NO_2 level by about 20% after accounting for meteorological variability (Forster et al., 2020).

Both NO_2 and $PM_{2.5}$ are the most anthropogenic activities sensitive pollutants in the atmosphere. It is well established that NO_2 is a traffic emissions tracer pollutant in the lower atmosphere (He et al., 2020). Some of the previous studies reported the percentage reduction of NO_2 and $PM_{2.5}$ over Europe and the USA, including the south and south-east Asia (SSEA) and the middle east (Bauwens et al., 2020; Broomandi et al., 2020; Dantas et al., 2020; Menut et al., 2020; Siciliano et al., 2020; Tobías et al., 2020; Zalakeviciute et al., 2020). The present study examined the relative changes of tropospheric NO_2 concentration from hemispheric scale to pollution hotspot cities. The cities were selected based on the lockdown's intensity (partial to complete lockdown). Over Europe and the USA, there are some cities where lockdown was partially practiced and in some cases, the lockdown wasn't implemented. The study aimed to find out the changes of NO_2 and $PM_{2.5}$ concentration between complete lockdown, partial lockdown, and no-lockdown cities. A comparison between NO_2 and $PM_{2.5}$ changes in these three categories of cities was made with reference to meteorological conditions. As aforementioned pollutants are quite sensitive to anthropogenic activities, city-wise population density and human modification data were also considered to explain the magnitude of pollutions changes.

The city environment plays an important role in determining the health conditions of urban populations, however, their relationship is generally ignored. Typically, urban health and social well-being have not been considered in most of the 'canonical' urban design theories (Böck, 2015; Rice et al., 2020). In most of the urban design theories, there are six broad sub-categories of urban design, namely, morphological, perceptual, social, visual, functional, and temporal dimensions (Carmona et al., 2010) which explicitly ignored the health dimension. During the Covid-19 lockdown, urban designers are highly concerned about human wellbeing compared to the pre-Covid-19 period. As such, urban designers can play a vital role in improving the population's health through their design decisions, and the mechanisms by which it affects individual health and social well-being (Azzopardi-Muscat et al., 2020). According to the WHO, 'Health in all policies' has been initiated as a 'health in all designs' strategy (Rice, 2019) and therefore, the urban designers need to focus on the health conditions of urban populations.

The above-mentioned studies are related to a large drop in air pollution concentrations due to pandemic and were based on a shorter period (i.e. around one month) and did not study systematically in the context of urban areas with lockdown efficacy, such as complete lockdown, partial or no-lockdown measures. This study aims to quantify the changes in pollutants, especially NO_2 and $PM_{2.5}$ concentrations across the most populous cities in Europe and the USA based on lockdown efficacy, and also emphasizing urban design, policy, and health status in the post Covid-19 era. In the present study, the tropospheric NO_2 and $PM_{2.5}$ concentration measurements made between March and May 2020 were compared with those made over the same months in 2019.

2. Materials and methods

Satellite-derived measurements of NO_2 and ground-based data $PM_{2.5}$ are used to provide a comprehensive estimate of the impact of lockdown on air pollution over major populous cities of Europe and the USA. Statistical analyses were also conducted for pollutant concentrations over specific cities using in-situ air pollution data. The cities were selected so that some cities represent complete lockdown whilst some represent partial or no lockdowns. The data are described in detail in the following sections.

2.1. Sentinel–5Ps TROPOMI data

Sentinel–5P satellite was launched in October 2017 that carries TROPOMI (Tropospheric Monitoring Instrument). The tropospheric vertical NO_2 column density data has been released from July 2018, which provides daily observations at a spatial resolution of 3.5 km × 7 km. Relatively, TROPOMI has a higher resolution than its predecessor Ozone Monitoring Instrument (OMI) with a spatial resolution of 13 km × 24 km. The Sentinel–5P is the first Copernicus mission satellite that monitors the atmosphere in a near-polar sun-synchronous (13:30 local solar time) orbit with an altitude of 817 km with an inclination angle of 98.7° and a swath of 2600 km. The TROPOMI instrument has four separate spectrometers, such as Ultraviolet (UV), UV Visible (UV-VIS), Near-infrared (NIR), and Short wave infrared (SWIR) (Griffin et al., 2019). They are used to monitor the concentration of ozone (O_3), methane (CH_4), formaldehyde (HCHO), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) (Veefkind et al., 2012). The NO_2 retrieval algorithm was developed by the Royal Netherlands Meteorological Institute (KNMI) that considers the ultraviolet and near-infrared bands (0.27–0.5 μm) and the algorithm was initially adopted from OMI based NO_2 retrieval (Boersma et al., 2004; Zara et al., 2018). Researchers have widely used the tropospheric NO_2 column density product. In the present study, this product from period January–May 2019 and 2020 (during COVID-19) were obtained from the TROPOMI sensor, and these data was accessed from the Google Earth Engine Data Repository (ESA, 2020; LPDAAC, 2020) (Table 2).

2.2. Ground observation data

Daily average NO_2 and $PM_{2.5}$ data from the ground stations located in the urban city centres in Europe and the USA were obtained from the Citizen Weather Observer Program (CWOP, 2020). In all, NO_2 and $PM_{2.5}$ data were obtained for five cities in Europe and six in the USA, which were selected based on their population density, global human modification (gHM), lockdown, and no-lockdown status. The European cities selected under lockdown are Paris, Milan, and Madrid, whereas no-lockdown or partial-lockdown cities are Stockholm and Warsaw. The cities of the USA selected under lockdown are New York, Boston, Springfield, whereas no-lockdown are Pierre, Bismarck, and Lincoln. In this study, we obtained NO_2 and $PM_{2.5}$ data during the time-frame March–May in 2019 and 2020 to perform a comparative analysis of impacts of different lockdown conditions on pollutant concentration during COVID-19.

2.3. ERA-5 based meteorological parameters

The meteorological conditions play a fundamental role in air quality by modifying the dispersive conditions of the atmosphere. To analyse the meteorological variability that has existed in the different cities during the lockdown period, the variables such as relative humidity (RH), precipitation, air temperature (2 m), wind speed, and boundary-layer height (BLH) were retrieved from the fifth-generation of European Centre for Medium-Range Weather Forecasts (ECMWF), global atmospheric reanalysis product (ERA5). All meteorological variables were at the daily temporal resolution, except BLH which is at monthly resolution. The BLH is the depth of air close to the Earth's surface and is affected by the resistance to momentum, heat, or moisture across the surface. When the BLH is low, higher concentrations of pollutants may develop. The relative humidity (RH) was taken at 1000 hPa level.

2.4. Gridded global human modification (gHM) and population density

The gridded global human modification (gHM) and population

Table 2
Details of satellite and ground data used for the period January–May over the span of 2015 and 2020.

Data used	Resolutions	Source
Sentinel–5P/TROPOMI (Tropospheric NO_2 concentration)	Spatial: 3.5 × 7 km Spectral: 0.27–2.3 μm Temporal: daily Duration: 2019–2020 (March–May)	ESA (2020)
In-situ observation: NO_2 and $PM_{2.5}$ from 11 cities	Temporal: daily Duration: 2019–2020 (March–May)	CWOP (2020)
ERA-5 (Humidity, precipitation, temperature, wind speed BLH)	Spatial: 9 km Temporal: daily Duration: 2015–2020 (March–May)	(ECMWF)
gHM (global human modification)	gHM-2016 30 arc-second (~ 1 km)	Kennedy et al. (2019)
Population density	GPWv411–2020 30 arc-second (~ 1 km)	SEDAC (2020)
Stringency Index, Containment and Health Index	Spatial: country-scale Temporal: daily Duration : 2020 (March–May)	Hale et al. (2021)

density data are available in 30 arc-second (~1 km) spatial resolution (Kennedy et al., 2019; SEDAC, 2020). These data were integrated to investigate the relationship between pollutants and anthropogenic activities. The gHM is a cumulative measure of human land modification related to five major anthropogenic stressors such as human settlement (population density, built-up areas); agriculture (cropland, livestock); transportation (major, minor, and two-track roads; railroads), mining and energy production, electrical infrastructure (power lines, night-time lights). The gHM ranges from 0 to 1, where 0 represents no modification, and 1 represents fully modified. This dataset was validated against high-resolution aerial or satellite imagery across the world and applied at national to global scale studies (Chu et al., 2020; Theobald et al., 2020).

2.5. Stringency index, containment and health index

The Oxford Coronavirus Government Response Tracker (OxCGRT) project has calculated several index such as Stringency, Containment and Health Index (Hale et al., 2021). Stringency index is a composite measure (0 to 100 scale) of nine of the response metrics, namely, school closures; workplace closures; cancellation of public events; restrictions on public gatherings; closures of public transport; stay-at-home; public information campaigns; restrictions on internal movements; and international travel controls. Whereas Containment and Health index is a composite measure of thirteen of the response metrics (Stringency nine indicators plus testing policy, contact tracing, wearing face mask, and vaccine rollout). A higher score denotes a stricter response (i.e. 100 = strictest).

2.6. Methods

The satellite-derived tropospheric NO_2 concentration (μmol m^{-2}) over the period March to May 2019 and 2020 (Table 2) was retrieved from the GEE platform using API code (Gorelick et al., 2017). A relative percentage deviation (RPD) was calculated to characterize the difference in tropospheric NO_2 concentration between 2019 and 2020 (March–May).

$$\mathrm{RPD} = \frac{\left(\mathrm{x_c} - \mathrm{x_p}\right)}{\mathrm{x_p}} * 100 \tag{1}$$

Where x_c and x_p are the mean NO_2 (March–May) in 2020 and 2019, respectively. The mean was computed by excluding the missing data. Analysis of the mean NO_2 and RPD was conducted both (i) globally to identify any anomalies due to the pandemic and (ii) over 11 major urban areas where lockdown restrictions were implemented (e.g. Paris, Milan, Madrid, New York, Boston, Springfield) and where they were less (partial) strictly enforced or even not implemented (e.g. Stockholm, Warsaw, Bismarck, Pierre, Lincoln). The analysis conducted over the urban areas aggregated the observations within a 20 km radius of the city centre. The RPD of the ground-based station for both NO_2 and $PM_{2.5}$ level was also computed using Eq. (1) but the x_p is the long-term mean over the period 2015–2019. The percentage difference in the meteorological parameters, such as RH, BLH, and precipitation is calculated between 2020 and the mean of 2015–2019 to investigate the link between the meteorological conditions and the concentration of pollutants in the atmosphere.

3. Results on variation of NO_2 and $PM_{2.5}$ level before and during lockdowns

3.1. Global variation of tropospheric NO_2 in 2019 and 2020 (march–may)

Analysis of the global variation of the mean NO_2 concentration in 2019 indicates that the mean NO_2 concentration over the Northern Hemisphere was 64 μmol m^{-2} in 2019 (Fig. 1a), but in 2020 it dropped to 52 μmol m^{-2} (decreased by 19%) (Fig. 1b). Some of the highest concentrations are found in Asia, particularly eastern China, where concentrations reach 300 μmol m^{-2} in 2019 (Fig. 1a) due to the high population density and industrial presence in the region indicated by the high human modification index (Fig. 1c). Countries with the highest NO_2 concentration are India, Europe, and the eastern USA, where the average NO_2 in 2019 was 230, 219, and 255 μmol m^{-2}, respectively.

Typically, over major pollutant hotspots countries, the spatial variation of NO_2 concentration was found lower in 2020 than in 2019 (Fig. 1b). In the northern hemisphere, the mode of industrial production and transportation was ceased from the 3rd week of January due to partial-to-complete lockdown. Therefore, this significant reduction of NO_2 was observed in 2020. As most of the COVID-19 hotspot countries are found over the northern hemisphere, it can be inferred that it directly impacts to reduce the average NO_2 level in the northern hemisphere compared to the southern hemisphere.

The maximum percent (%) dropdown in NO_2 concentration over the northern hemisphere was up to 40%, but it varied mostly between 10% and 40% (Fig. 1b) over several parts of the developed nations, including China and India. The areas with a higher reduction in NO_2 concentration are co-located with higher gHM and population density (Fig. 1c). There was also a strong connection of relative percentage deviation (RPD) of NO_2 in 2020, co-located with higher coronavirus infected countries. The central eastern part of China acts as a pollution hotspot of Southeast Asia, where the highest negative RPD of atmospheric NO_2 level (20–40%) was found. India, the Eastern Mediterranean region, Western Europe, and the Eastern USA, among others, have accounted highest negative RPD, which is also positively connected with Covid-19 affected urban areas.

3.2. Variation of NO_2 and $PM_{2.5}$ level in European cities

Countries in Europe also announced lockdowns to curb the spread of COVID-19. The French, Italian and Spanish governments implemented lockdowns from March 17th, 9th, and 14th, respectively. As a result, in northern France, tropospheric NO_2 density which was typically exceeded >150 μmol m^{-2} in 2019 was decreased by 40% (Fig. 2) on average to 50–150 μmol m^{-2} in 2020. Ground observations of NO_2 and $PM_{2.5}$ in Paris also support this finding, revealing a significant decrease in NO_2 concentration by 51%. As evident at other sites, a reduction of $PM_{2.5}$ concentration was also observed by ~15% (Table 3). A similar situation is observed in Milan, northern Italy, where the mean NO_2 concentration was decreased by 31% (Fig. 2), with an average between 50 and 300 μmol m^{-2} in 2019 to 100 and 200 μmol m^{-2} in 2020. In-situ NO_2 and $PM_{2.5}$ observations exhibit both NO_2 and $PM_{2.5}$ concentrations decrease by 46% and 19.5%, respectively in 2020. In Madrid (central Spain), the satellite-derived average NO_2 concentration was decreased by 27% (Fig. 2), which was lower than the 50% measured using in-situ data. Typically, reduction in NO_2 levels estimated from satellites and observed from ground station measurements are not equivalent, and the latter showed a higher percent reduction. This can be due to the way NO_2 is measured, one measures the vertical density on a surface (i.e. TROPOMI), and the other represents the mass in a volume on the surface. Both Milan and Paris cities have exhibited very high gHM (> 0.8) whilst Madrid has exhibited ~0.52 gHM (Fig. 3). The mean population density recorded in Madrid, Milan, and Paris as 5816, 5400, 15,779 person/sq.km, respectively (Fig. 3). The highest decreases in NO_2 concentration over Milan and Paris were concurrent with the highest gHM and population density.

Conversely, few European countries either have partial lockdown (Warsaw in Poland) or no lockdown (Stockholm in Sweden). It was evident that these two cities, such as Warsaw and Stockholm, revealed the least reduction in NO_2 concentrations, which decrease by 7% and 19% respectively in 2020 (Fig. 2). The corresponding ground observed NO_2 concentrations exhibited a decrease of 20% and 39%, respectively in 2020. A reduction in measured $PM_{2.5}$ concentration in Stockholm was

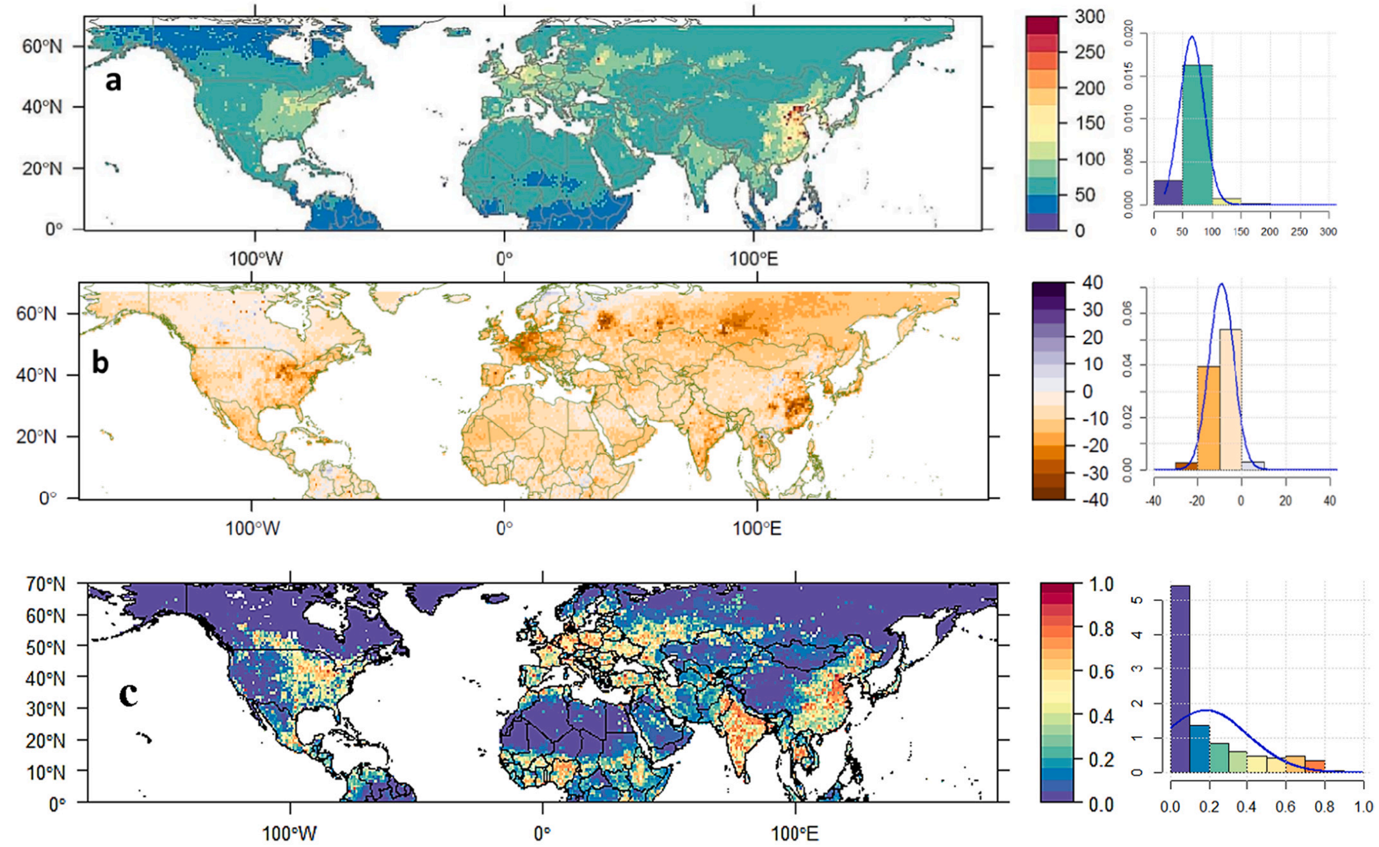

Fig. 1. Present the mean tropospheric NO_2 concentration (μmol m^{-2}) in 2019 (1st March–18th May) (a), the percent deviation of NO_2 concentration in 2020 (b), and gHM (c).

also found least among other study sites (31.88%). The cities of Stockholm and Warsaw have exhibited very high gHM (~ 0.75) where population density was recorded as 3843 and 4398 person/sq.km, respectively (Fig. 3), which could explain the lowest decreases in NO_2 concentration besides partial or no lockdowns.

The ground-station based weekly average NO_2 concentration for 2019 and 2020 showed that NO_2 levels were lower in 2020 in all five cities (Madrid, Milan, Paris, Stockholm, and Warsaw) of Europe during the effective lockdown period in 2020 (i.e. 8th March–8th May) (Fig. S1). The ground-station based weekly average $PM_{2.5}$ concentration also showed lower levels of $PM_{2.5}$ in all selected five cities except some exceptions weeks in April 2020 in Madrid and Milan (Fig. S1). The detailed statistics of RPD of NO_2 and $PM_{2.5}$ levels have been presented as a box plot in Fig. 4, representing city-wise mean, median, minimum, and maximum.

3.3. *Variation of NO_2 and $PM_{2.5}$ level in cities of USA*

In the USA, the government has imposed lockdowns only in severely affected cities like New York, Boston in Massachusetts, Springfield in Illinois on 22nd March, whereas it was not imposed in other cities such as Bismarck in North Dakota, Pierre in South Dakota, Lincoln in Nebraska. In New York, the mean tropospheric NO_2 density was typically exceeded >250 μmol m^{-2} in 2019, which was later decreased by 26.6% (Fig. 5) on average to 150–250 μmol m^{-2} in 2020, whilst ground-based measured NO_2 revealed a decrease by 25%. A similar situation was observed in Boston and Springfield, where the mean NO_2 concentration decreased by 18.3% and 6%, respectively (Fig. 5) whilst ground-based measured NO_2 revealed a decrease of 35% and 31.4%, respectively (Table 4; Fig. 4). In contrast, other cities such as Bismarck, Pierre, and Lincoln, where there were no lockdowns implemented, revealed that the mean tropospheric NO_2 concentration was decreased by only 3%, 6.9%, and 7.6%, respectively (Fig. 5), and these relatively lower amounts of reduction are indicative of least impact due to no lockdown during COVID-19 pandemic. In addition at the Pierre site, the ground-based measured NO_2 revealed even an increase of 15.8% (Table 4; Fig. 4). Referring to ground-based measured $PM_{2.5}$ concentration, it dropped to 10%, 7.8%, and 15.8% in New York, Boston, and Pierre, respectively in 2020 compared to 2019. However, the $PM_{2.5}$ concentration was increased to 2.4%, 7.6%, and 7.9% in Springfield, Bismarck, and Lincoln, respectively (Table 4; Fig. 4) showing a clear impact of lockdown measures.

The urban conurbations such as New York, Boston, and Springfield exhibited gHM as 0.38, 0.88, and 0.60, respectively. Highest population density exhibited about 50,000, 15,000, and 5000 person/sq.km, respectively (Fig. 3), whereas the mean population density recorded in New York, Boston, and Springfield was 15,650, 4891, and 462 people/sq.km, respectively (Fig. 3). The highest decrease in NO_2 concentration over New York, Boston, and Springfield could be associated with the highest gHM and population density. The cities such as Pierre, Bismarck, and Lincoln exhibited the mean gHM as 0.30, 0.38, and 0.33, respectively, and the average population density exhibited about 527, 1554, and 2606 person/sq.km respectively (Fig. 3). The decreases in NO_2 concentration over all these three cities are minimal, which could be attributed to lower gHM and population density, including no lockdown measures undertaken during COVID-19.

The ground-based station measurements for weekly average NO_2 concentration demonstrated lower NO_2 levels in 2020 (during the effective lockdown period) compared to 2019 in cities such as New York, Boston, Springfield, and Nebraska (Fig. S2). However, Pierre showed a higher NO_2 concentration in 2020 compared to 2019, and an insignificant change was found in Bismarck, which could be attributed to no

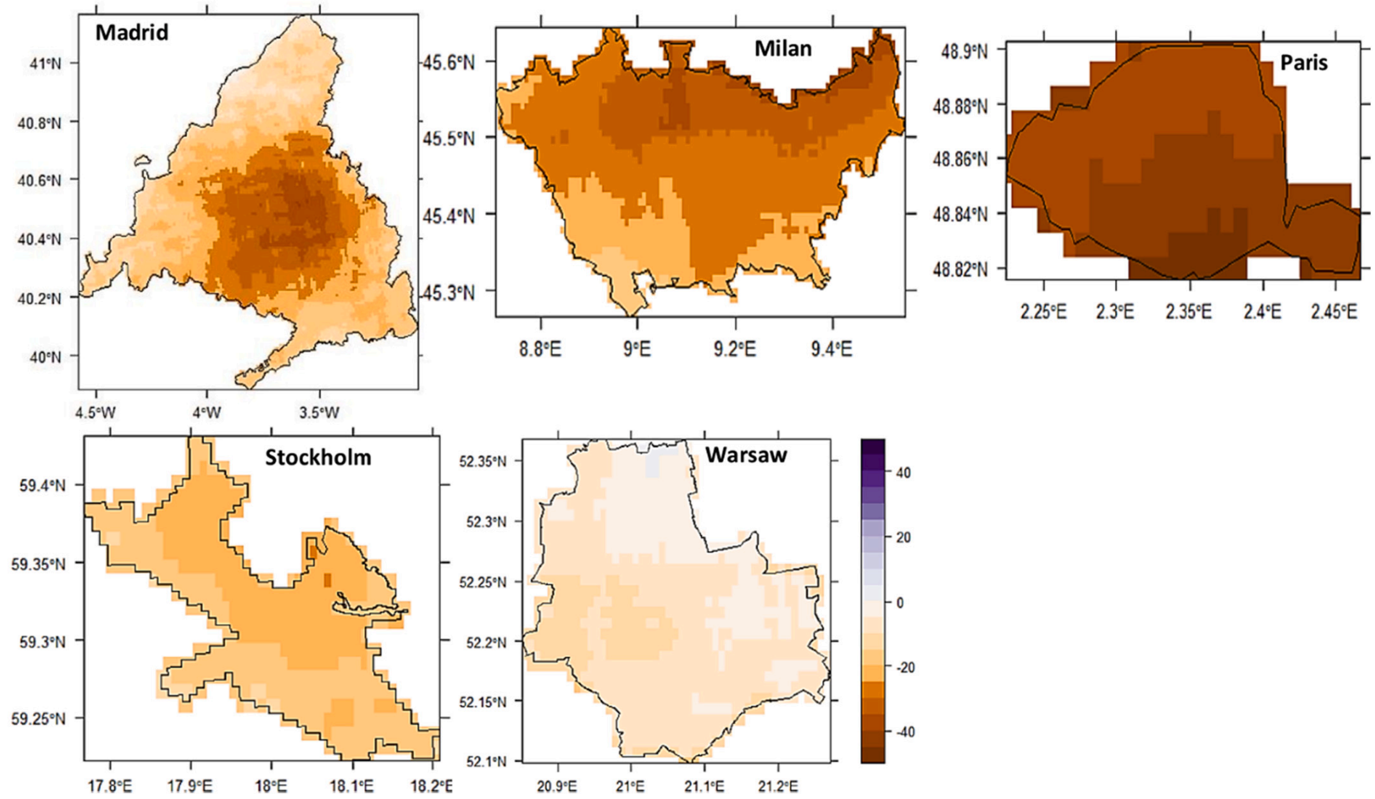

Fig. 2. Present RPD of mean tropospheric NO_2 concentration during effective lockdown period in 2020 (i.e. 8th March–8th May) across five select cities in Europe. The upper panels showed the cities with lockdowns (Madrid, Milan, and Paris), and the lower panel showed cities without or partial lockdown (Stockholm, Warsaw).

Table 3
Average relative percentage deviation (RPD) and standard errors (± se) of NO_2 and $PM_{2.5}$ concentration in 2020 (during lockdown periods) in comparison to the observation of 2019 during the same time frame. The RPD was derived only for the lockdown periods, which varied from country to country in Europe.

Ground station	RPD (%) (satellite-derived)	RPD (%) in surface station		Lockdown Periods
	NO_2	NO_2	$PM_{2.5}$	
Paris, France	−40 (± 0.05)	−50.88 (± 4.28)	−15.44 (± 4.83)	24th March to 8th May
Milan, Italy	−31 (± 0.11)	−45.94 (± 3.87)	−19.51 (± 5.82)	09th March to 8th May
Madrid, Spain	−27 (±0.11)	−49.82 (± 2.86)	0.65 (±4.69)	14th March to 8th May
Stockholm	−19.41 (±0.10)	−39.27 (±4.58)	−31.88 (±5.54)	No lockdown (09th March to 8th May)
Warsaw	−6.86 (±0.10)	−20.24 (±4.62)	0.87 (±4.81)	Partial lockdown (13^{h} March to 11th April)

lockdown measures in the pandemic. The weekly average $PM_{2.5}$ concentration in 2020 also showed reduced levels in cities such as New York, Boston, and Pierre in most of the weeks during the lockdown period (Fig. S2). However, Springfield, Lincoln, and Bismarck indicated a higher $PM_{2.5}$ concentration in 2020 than in 2019, which could be attributed to no lockdown measures. The detailed statistics of RPD of NO_2 and $PM_{2.5}$ levels have been shown in Fig. 5.

3.4. *Variation in NO_2 and $PM_{2.5}$ in relation to meteorological conditions*

Meteorological variables have been reported to impact the concentration of atmospheric pollutants. Hence, in our study, we made a comparison between meteorological variables (relative humidity (RH), boundary-layer height (BLH), air temperature, precipitation and wind speed) measured in 2020 with the meteorological variables (average condition) of 2015–19 (Fig. 6). The result indicated a decrease in RH across selected European cities by 3–17% except for Madrid and these conditions might be appropriate for decreasing pollutants. The BLH was mostly reduced in Milan and Madrid (complete lockdown cities) by 3 and 22%, respectively, signifying stable boundary layer and stationary air formation. However, an insignificant change was found in Paris. These conditions are suitable for increasing the concentration of pollutants. Partial to no lockdown cities such as Stockholm and Warsaw demonstrated a significant increase in BLH by 13 and 46%, respectively, which might favor in decreasing the atmospheric pollutants. The precipitation displays mostly decreasing patterns except for Madrid and Stockholm. So, it might not play any role in reducing large-scale atmospheric pollutants during the lockdowns. However, increasing pattern of precipitation in Madrid and Stockholm could have possible impacts on lowering the pollutants. Changes in air temperature were insignificant (within 10%) over cities of Europe. The mean wind speed increased by 51–205% in all selected cities of Europe that might cause the vertical mixing of gases and dispersion of pollutants. Overall, the meteorological conditions might have a smaller role in reducing the vertical distribution of pollutants in Europe's urban areas.

Compared to the average of 2015–2019, there was a decrease in RH by 1.5–10% in 2020 across all six cities in the USA and these conditions might be suitable for decreasing atmospheric pollutants. The mean wind speed was decreased by 28–53% especially over lockdown cities of the USA (i.e. New York, Boston, and Springfield) that indicating weaker mixing of gases and high levels of atmospheric pollutants. However, the wind speed was found to be increased in no-lockdown cities by 4% in Pierre and 66% in Lincoln and suggesting the dispersion of atmospheric pollutants. The BLH was increased by 5–22% in all the selected cities, representing an unstable boundary layer and the condition was ideal for

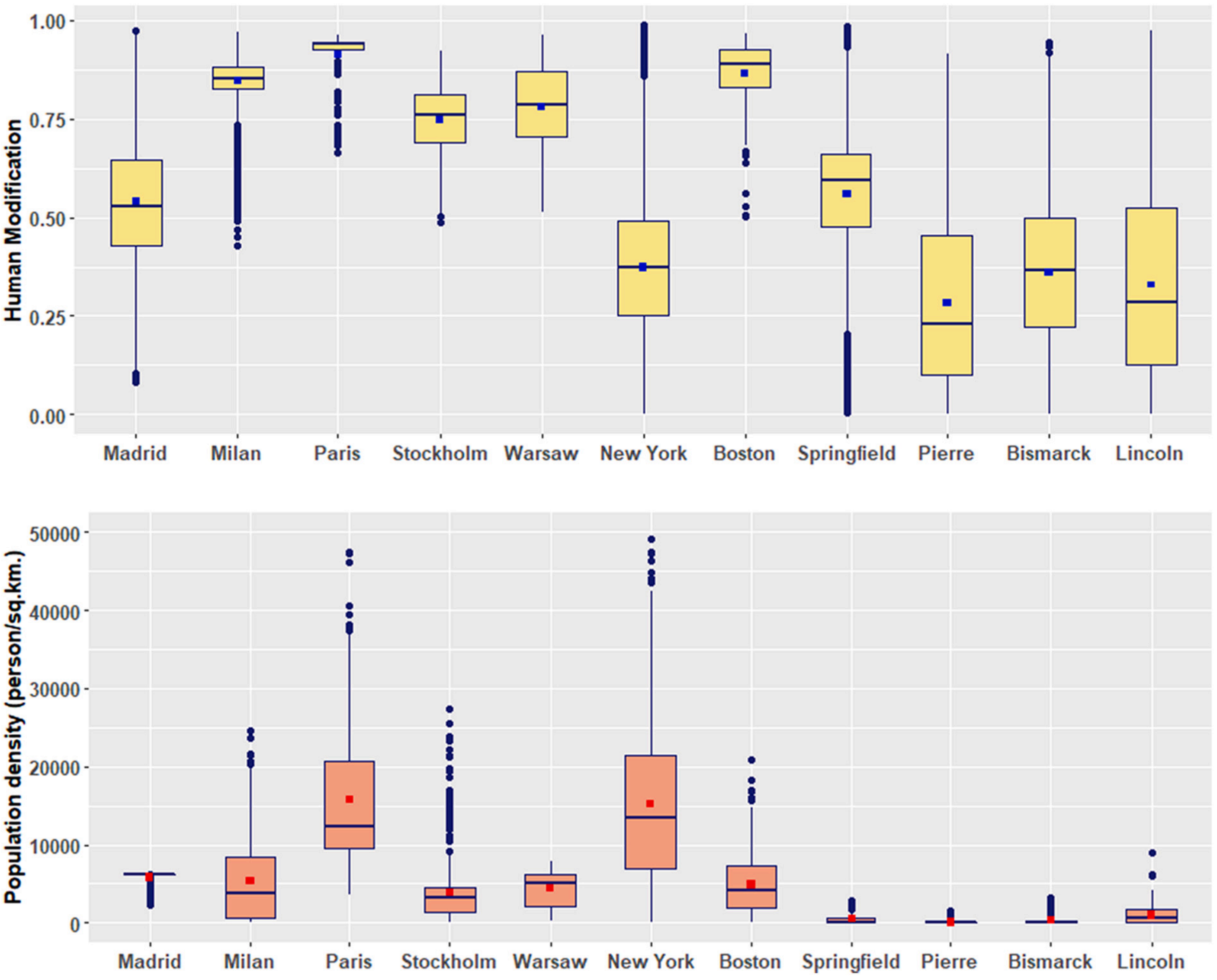

Fig. 3. Present the global Human Modification (gHM) (upper panel) and population density (lower panel) in 11 cities across Europe and the USA.

reducing atmospheric pollutants. The precipitation has shown mainly decreasing patterns by 6–32% except for New York (+ 5.5%) and Boston (+ 9.3%), and these conditions might not be suitable for decreasing large-scale atmospheric pollutants during the lockdowns. However, increasing precipitation patterns in New York and Boston could have some impacts on lowering the atmospheric pollutants. Air temperature changes were found between 4% and 13% over the selected cities of the USA. Therefore, the reduced vertical distribution of the pollutants in the USA's urban areas might be also associated with meteorological variability, albeit to a smaller extent.

3.5. Covid-19 policy response (Stringency, Containment and Health Index)

The Stringency index and Containment and Health index are the measures of how lockdown and health-related policy were considered to restrict the proliferation of COVID-19 (Fig. 7). Though these data frames are in-country scale, it can be inferred that the efficacy of lockdown has been reflected in the stringency index. For instance, Italy (lockdown) and Sweden (no-lockdown) showed the highest strictest response (90) and lowest strictest response (60), respectively (Fig. 7a). A similar pattern was also noticed in the containment and health index (Fig. 7b). These indices have also a correspondence with the pollution level of NO_2 and $PM_{2.5}$. In normal conditions (after Covid-19 recovery), some of these measures (mainly Stringency Index) could be practiced on a city scale and a day of a week. This could be an alternative or sustainable way to step down extreme ground pollutions levels without compromising the economic progress of countries.

4. Discussion

4.1. Efficacy of lockdown and reduced anthropogenic emissions across the cities

Due to the ongoing COVID-19 pandemic, all types of human activities and fumes from sclerotic traffic and the burning of fossil fuels have been partial to total closed as a measure of curbing the spread of disease by imposing strict lockdown. However, it could be considered as a silver lining regarding anthropogenic emissions from an air quality point of view. It can be depicted that an inverse relationship between the economy and the environment. The environment is healing at the cost of the economy since the core economy is dependent on fossil fuels and industries. The nationwide lockdown has significantly reduced the consumption of fossil fuels. Subsequently, emissions of atmospheric pollutants (NO_2 and $PM_{2.5}$, among others) have also been decreased across the world. In this study, satellite-derived (TROPOMI) tropospheric NO_2 level (from surface up to ∼10 km) was analyzed across the major cities in Europe and the USA to quantify and explain the spatial variation and temporal changes. The key findings indicate that the satellite-derived tropospheric density of NO_2 level declined sharply (18–40%) in March–May 2020 against the same period in 2019 (Table 5) over urban atmosphere across the globe owing to the closure of industries, non-essential business, transport systems, institutes, offices, and citizen mobility.

Among selected 11 cities, the highest dropdown was obtained from Paris, France (40%), whilst the lowest dropdown was obtained from urban areas located in Bismarck in North Dakota (3%). A dropdown of

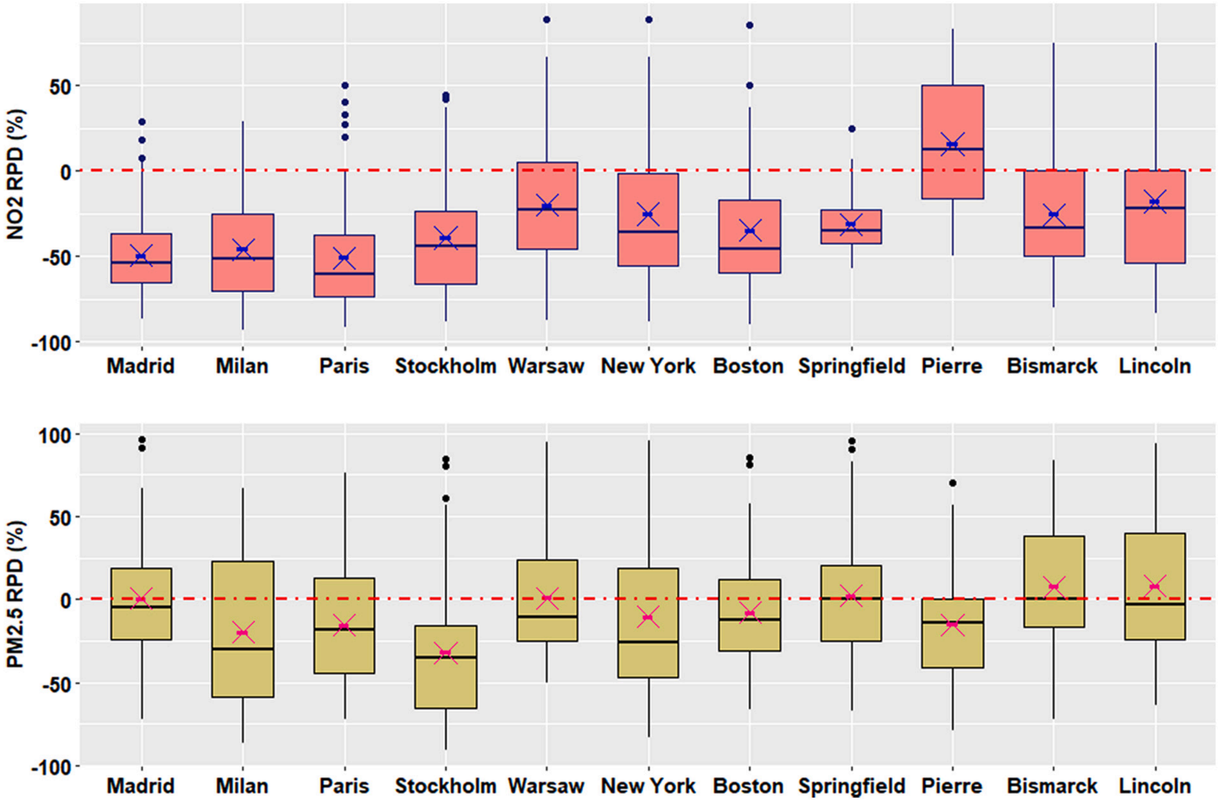

Fig. 4. The box plot represents the RPD distribution of ground-stations NO_2 and $PM_{2.5}$ concentration in cities of Europe (8th March–8th May) and the USA (22nd March–31st May).

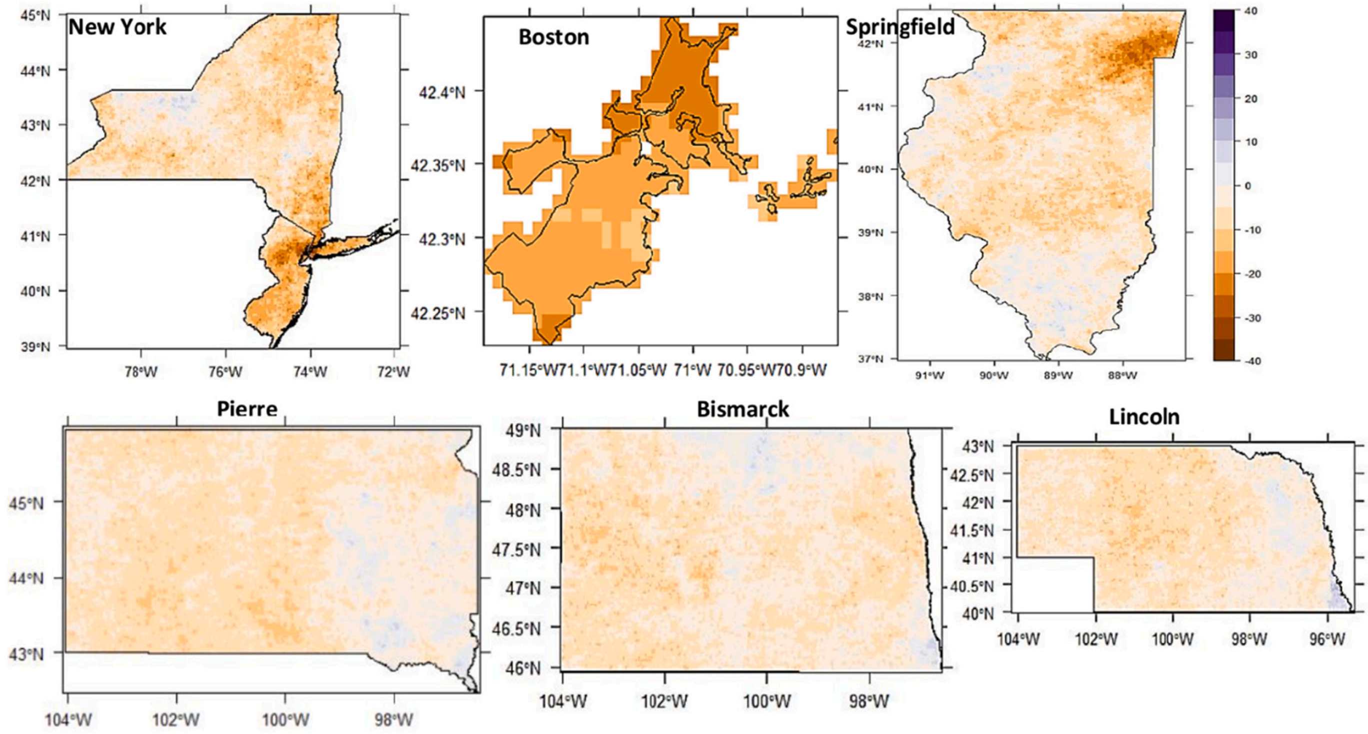

Fig. 5. Present RPD of mean tropospheric NO_2 concentration during the effective lockdown period in 2020 (i.e. 22nd March–30th May) across six select cities in the USA. The upper panels showed the cities with lockdowns (New York, Boston, Springfield), and the lower panel shows cities without lockdown (Pierre, Bismarck, Lincoln).

Table 4

Average relative percentage deviation (RPD) and standard errors (± se) of NO_2 and $PM_{2.5}$ concentration in 2020 (during lockdown periods) in comparison to the observation of 2019 during the same time frame. The RPD was derived only for the period from 22nd March to 30th May.

Ground station	RPD (%) (satellite-derived)	RPD (%) in ground station		Lockdown periods
	NO_2	NO_2	$PM_{2.5}$	
New York	−26.57 (± 0.12)	−25.25 (± 5.13)	−10.32 (± 6.17)	22nd March to 30th May
Boston	−18.28 (± 0.15)	−34.96 (± 4.58)	−7.80 (± 4.44)	
Springfield	−6.02 (± 0.054)	−31.43 (± 1.96)	2.40 (± 4.68)	
Pierre	−6.89 (± 0.04)	15.79 (± 5.06)	−15.80 (± 4.43)	No-lockdown
Bismarck	−2.96 (± 0.046)	−25.62 (± 5.22)	7.65 (± 4.59)	
Lincoln	−7.6 (± 0.04)	−18.44 (± 5.22)	7.94 (± 5.63)	

NO_2 level between 27% (Madrid) and 40% (Paris) was obtained from European cities, such as Madrid, Milan, London, and Paris (Table 5). However, partial to no-lockdown cities such as Warsaw and Stockholm exhibit a decrease in mean NO_2 level by 7%, and 19% respectively, which is relatively lower than other European cities, and it might be related to non-closures of surface transport and industrial activities. The USA cities with lockdowns such as New York, Boston, and Springfield exhibit a decrease in NO_2 between 6% (Springfield) and 27% (New York). Whereas in contrast, a relatively lower reduction in NO_2 (3 to 7.5%) was observed from the cities with no lockdowns such as Pierre, Bismarck, and Lincoln, which could be attributed to business as usual anthropogenic activities related to surface transport and industrial activities. However, a slight decline in NO_2 concentration in these cities might be due to the slowdown of human activities due to fear of corona spread. The comparison between cities showed that reduced pollutants mainly depend on the city-level confinement conceived and their different policies affecting anthropogenic emissions.

As compared to our findings on the dropdown of NO_2 over European cities, the ESA has reported (ESA, 2020; Muhammad et al., 2020) a reduction of about 47–54% in European cities (Milan, Rome, Madrid, and Paris), which used TROPOMI sensors to determine the NO_2 density over the time-frame of 25 March–20 April 2020 as compared to the same time-frame in the last year 2019 (Collivignarelli et al., 2020; Kanniah et al., 2020; Mahato et al., 2020; Tobías et al., 2020). These estimates' differences were mostly attributed to the time-frame used by our study (average between March–May 2020) and by ESA (i.e. average between 25 March–20 April 2020) (ESA, 2020). Another study from Barcelona and Madrid (Spain) also reported that the NO_2 concentration was decreased by 50% and 62%, respectively, under COVID-19 lockdown during March 2020 (Baldasano, 2020). Furthermore, we have analyzed NO_2 and $PM_{2.5}$ levels using the ground-based station observation data, and these data have also indicated a dropdown in NO_2 (20–51%) and $PM_{2.5}$ (15–32%) levels across the major cities in Europe and the USA. It was also noticed that the atmospheric NO_2 is much more sensitive than $PM_{2.5}$ with respect to vehicles, power plants, and industrial emissions; that's why the NO_2 percent deviation was higher than the $PM_{2.5}$. The public mobility for transport and other categories were shown in Table 5. The data indicated that transport was reduced by 49%, 69%, 65%, 80%, and 76% (Table 5) over New York, Spain, Italy, France, and the UK, respectively (Google, 2020; Muhammad et al., 2020) which was connected with this unprecedented reduction of NO_2. Whereas the cities with no lockdown revealed an increase in transport category by 6% (Lincoln) to 17% (Pierre) as given by mobility index (Table 5).

The key findings of the study demonstrated significant reductions (in varying magnitude) of troposphere and ground observed NO_2 and $PM_{2.5}$ from a semi-global or hemisphere to city (anthropogenic emission hotspot) scale. Specifically, most populated and anthropogenically modified regions (i.e. eastern China, India, Europe, and the eastern USA) of the northern hemisphere are associated with a sizable reduction of NO_2 concentration due to sudden partial-to-total restriction of transport and

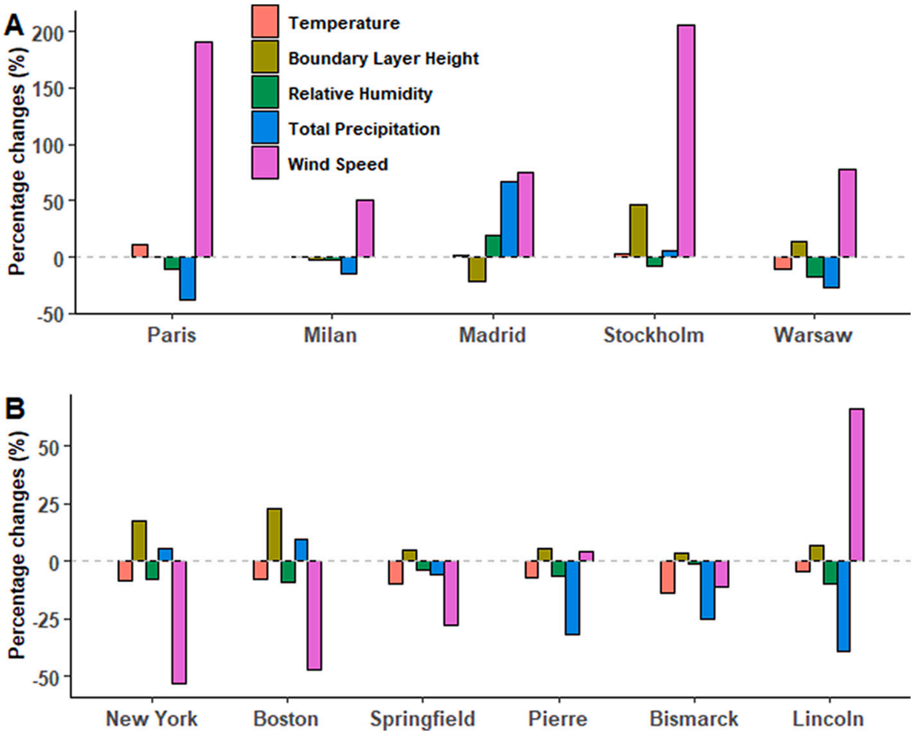

Fig. 6. Percent changes in meteorological conditions such as RH, BLH, air temperature, precipitation, and wind speed between the 2020 and 2015–19 (i.e. March–May) based on the ERA-5. (A) represents five urban cities of Europe and (B) represents six urban cities of the USA.

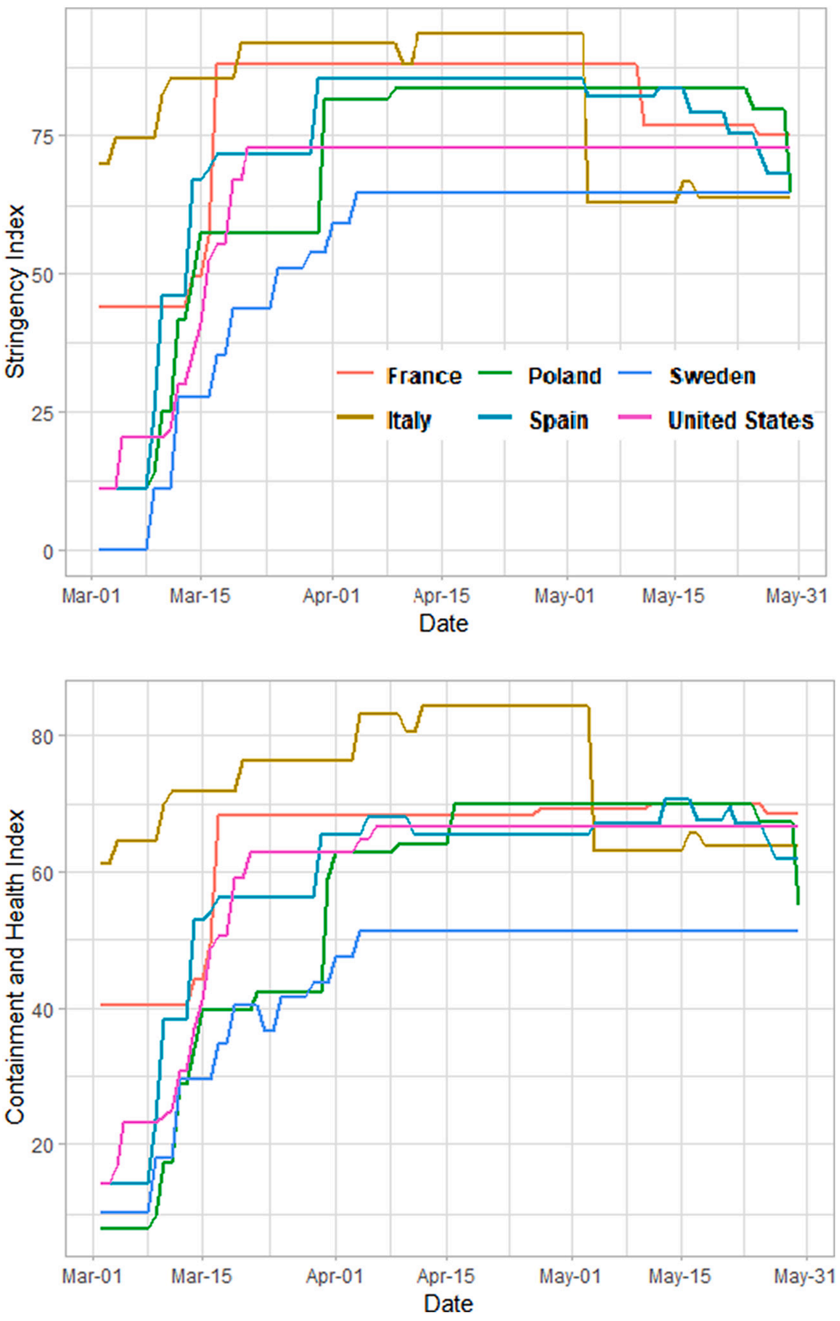

Fig. 7. Stringency Index (a) and Containment and Health Index (b) in the scale of 0 to 100 during March to May 2020 across the European countries and the USA.

industrial mode of production. The hemispheric dropdown of NO_2 is also consistent with the local and regional studies conducted over SSEA, middle east, Brazil, Europe, and North America which reported a reduction by 20–40% (Acharya et al., 2021; He et al., 2020; Isaifan, 2020; Kanniah et al., 2020; Kumar et al., 2020; Le et al., 2020; Mahato et al., 2020; Pei et al., 2020). Similarly, ESA (2020) and Menut et al. (2020) found a substantial decrease in NO_2 concentration in western Europe (47–54%) whilst Bauwens et al. (2020) reported a decline over eastern parts of the USA (19–28%). Similarly, numerous studies also reported a decrease in $PM_{2.5}$ concentration by 19–54% across urban areas of SSEA, middle east, Brazil, Europe, and North America (Bao & Zhang, 2020; Chauhan & Singh, 2020; Kumar et al., 2020; Siciliano et al., 2020; Tobías et al., 2020; Venter et al., 2020; Xu et al., 2020; Zalakeviciute et al., 2020). Our results revealed that the percent reduction for NO_2 and $PM_{2.5}$ was consistent with above findings, which showed a reduction between 18 and 40% and 15–32%, respectively for partial to complete lockdown implemented cities.

The pervasive decline in atmospheric NO_2 and $PM_{2.5}$ was associated with complete to total lockdown cities while no-lockdown cities revealed a lower degree of reduction (in some cases $PM_{2.5}$ even increased) of these pollutants. The reductions of pollutants in no-lockdown cities of the USA and Europe might attribute to the boundary effects of associated restricted regions. The level of NO_2 was substantially lower during lockdown because it is a primary pollutant which is more strongly associated with traffic, whereas $PM_{2.5}$ is a secondary pollutant constituted in the atmosphere from a different source of emissions (Bekbulat et al., 2020).

A higher average wind speed and lower humidity were exhibited over EU cities (except Madrid) during the lockdown period compared to the similar duration from the average of 2015–2019 meteorological conditions. Average wind speed and RH were found in a positive association with atmospheric NO_2 and CO concentration and a contrast

Table 5

The % reduction of the satellite-derived tropospheric density of NO_2 level across 11 major urban areas during the partial-to-total lockdown in 2020 against 2019 throughout March–May. Mobility index (in %) as retrieved from google tracking data as of 8th May (European cities) and 31st May (cities in the USA). The cities marked by bold represent partial or no-lockdown.

Cities	% Reduction in NO_2	Mobility index (Google, 2020)					
		Transport	Grocery /Pharmacy	Retail and Recreation	Work place	Parks	Residential
Paris, France	−40	−80	−58	−83	−82	−57	38
Milan, Italy	−31	−65	−28	−65	−48	−20	24
Madrid, Spain	−27	−69	−34	−83	−68	−36	33
Stockholm, Sweden	**−19**	**−37**	**−4**	**−22**	**−36**	**63**	**12**
Warsaw, Poland	**−7**	**−44**	**−6**	**−30**	**−31**	**35**	**11**
London, UK	−30	−76	−27	−79	−81	32	35
New York, USA	−26.5	−49	−11	−43	−21	79	08
Boston	−18.2	−46	−13	−29	−17	102	07
Springfield	−6.0	−29	−12	−30	−17	115	05
Pierre	**−6.9**	**17**	**24**	**6**	**−5**	**284**	**0**
Bismarck	**−3.0**	**−6**	**5**	**−5**	**−6**	**181**	**−1**
Lincoln	**−7.6**	**6**	**4**	**−15**	**−8**	**140**	**3**

relation with temperature over Poland (Cichowicz et al., 2017). Despite higher wind speed and lower RH, a significant reduction of NO_2 in EU cities directly indicating the effects of partial-total lockdown. The air temperature, wind speed (except Springfield and Bismarck), and RH were significantly lower compared to the average of 2015–2019 meteorological conditions in the USA cities. Therefore, mixed effects of the meteorological parameter were attributed.

Results indicated a sudden decline of atmospheric NO_2 over urban areas in Europe and the USA during the lockdown. Furthermore, a strong relation between tropospheric NO_2 concentration and the number of fatality cases of COVID-19 has been found over cities in Italy, Spain, and France (Ogen, 2020). Nevertheless, meteorological variability is an essential factor to consider when assessing NO_2 and $PM_{2.5}$ concentrations during lockdown duration because it modifies the atmosphere's dispersive conditions (Baldasano, 2020). In this context, we found that meteorological conditions' variability might play a smaller role in reducing atmospheric pollutants. It was also reported that tropospheric NO_2 differences were only by ~15% due to changes in meteorological conditions over several urban areas of North America (Goldberg et al., 2020). In Barcelona and Madrid (Spain), the large-scale drop in NO_2 concentrations during the lockdown was also linked to a mixture of good and bad dispersive meteorological conditions (Baldasano, 2020). Hence, such large-scale changes in pollutants might not be possible by small-scale variability in meteorological conditions across urban areas globally (Schiermeier, 2020). However, there was a profound indication that decreased atmospheric pollutants concentration was primarily due to human activity (Muhammad et al., 2020; Navinya et al., 2020; Tosepu et al., 2020).

4.2. Lockdown and its association with clean air policies and premature deaths

Air pollution is one of the rising threats affecting public health, specifically in urban and industrial regions (Fowler et al., 2020). In the last three decades (1990–2020), the air quality has steadily improved over cities in Europe and the USA due to the effective practice of roust clear air policies at various governance levels (Crippa et al., 2016; EEA, 2018; EPA, 2019). Despite this improving trend, the European Union (EU) air quality standard for protection of human health (e.g. PM, NO_2, and Ozone (O_3)) were not being fulfilled in the large parts of the EU, mostly in the urban area where more than 70% of EU population lives (*EEA Environmental Indicator Report,* 2018). These air pollutants are mainly attributed to emissions from automobiles, industry, agriculture, and commercial/residential. Therefore, air pollution has been considered as one of the largest environmental health hazards over EU-28, resulting in respiratory issues and premature deaths of about 379,000 people in 2018 (EEA, 2020b). However, it represents about 13% reduction in premature deaths both in Europe and the EU-28, compared with 2009 level and a reduction of about 54% in premature deaths compared to 1990 level in EU-28 (EEA, 2020b). Whereas, the premature deaths due to ground-level O_3 for the EU-28 in 2018 compared to 2009 was increased by 24%. This was due to the strong influence of high temperatures during the summer season on O_3 concentration particularly in 2018 (EEA, 2020b). The Environmental Action Programme (EPA, 2013, 2020) was also setup guidelines for improving the outdoor air quality standard over Europe and to remain within the WHO limit. In the USA, more than 100,000 premature deaths were reported due to air pollution in 2005. Due to stringent emission control policies, a reduction in premature deaths by 13%, 19%, and 35% was reported due to $PM_{2.5}$ and/or Ozone, SO_2, NO_x, respectively from 2005 to 2018 (Dedoussi et al., 2020). Notably, during the lockdown period in Europe, it was estimated that 2190 (1960–2420) premature deaths were averted due to reduced $PM_{2.5}$ concentration. It also projected a reduction of premature deaths between 13,600 and 29,500 depending on the immediate resumption (until May in 2020) to permanent lockdown (until December in 2020) scenarios, respectively (Giani et al., 2020).

During the lockdown, mostly the primary pollutants' emissions were declined, and especially the NO_2 concentration was decreased by 50% from its peak observation in both Europe and the USA (Acharya et al., 2021; Fowler et al., 2020). Nevertheless, several cities and urban regions faced exceedances of the regulated air quality limits where a more integrated and ambitious clear air approach is required (Kuklinska et al., 2015). The air quality was improved in many cities and regions of Europe and the USA due to stringent restrictions of transport and industrial production (Baldasano, 2020; Berman & Ebisu, 2020; Dang & Trinh, 2020; Zangari et al., 2020). First time since World War-II, the lockdown come up with an opportunity to practice or experiment with the trade-off between air quality and sustainable or green mode of economic production.

4.3. Lockdown and emerging urban policies

Major cities in the European Union (EU) and the USA have become the epicentres of the COVID-19 pandemics because of their dense population, transport networks, economic activity, national and international trades. All these have facilitated the rapid community transmission of the virus and acts as an entry point for countrywide transmission. City administration is the local unit of government closest to people, who are responsible for reaching people and making them aware of the guidelines to reduce the risk of COVID-19 infection and implementation of national policies related to curing and prevention of COVID-19 spread. Furthermore, city administration plays a key role in providing the essential services, regulating the lockdown measures, addressing social, cultural, environmental, and economic dimensions, and contribute to national preparedness and response plans against COVID-19. To overcome the COVID-19 challenge, the EU and the USA have formulated several urban policies. Some of the key urban planning for strengthening cities' economic, social and cultural fabrics are emphasizing core services, affordable housing, public amenities, public spaces, integrated green and blue spaces, urban design, and city-level geospatial data (Honey-Rosés et al., 2020; UNICEF, 2018). As urban areas are vulnerable, the idea of 'sustainable cities and communities' envisaged in Sustainable Development Goals (SDGs)-11 needs to be revisited and implemented. The connection between infrastructure, active mobility, and health can be strengthened to build urban resilience against future pandemics and emergencies. In this context, the United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP, 2020) emphasizes five crucial strategies, such as (i) plan compact cities based on public transport and active mobility, (ii) prioritize active mobility for public transport, (iii) develop infrastructure for active mobility, (iv) develop resting areas and public parks, and (v) improve environments along walking routes by planting trees and beautification. A new urban paradigm towards green, resilient and smart cities can be emphasized and some of the key policies discussed by Organization for Economic Co-operation and Development (OECD) are asymmetrical impacts, economic and social shock, active mobility by enhancing accessibility, social and structural inequality, digitalization, environmental awareness, governance, resilience, and Global agendas (e.g. SDGs) (OECD, 2020). Some of these policies are also suggested by Sharifi and Khavarian-Garmsir (2020) to deal with future emergencies (Refer to Table 2 given in Sharifi and Khavarian-Garmsir).

4.4. Urban design and prioritizing human health and environment after Covid-19 era

After Covid-19, the urban design needs to be embedded with human health at its core because more than half of the world population is living in an urban setup. The architecture and urban design leading to improvement in urban population health would be in line with the WHO motto stating 'health in all designs' strategy (Rice, 2019) which indicates 'health in all policies' to ascertain strong health component in all policy and decision-making process. Recent estimates showed that nearly 7 million death worldwide per year occurred due to air pollution (WHO, 2020) and mostly from urban areas. These numbers could be preventable through the enactment of urban design and policy. Besides air pollution, there are many other urban risks (e.g., exposure to hazards and pandemics, poor local governance, environmental degradation, overstretching of resources, climate risks), which impact public health and societal well-being (UNDP, 2020). Hence, the urban design must prioritize improving human health in the city environment by reshaping urban planning in terms of sustainability as well as prioritizing nature conservation and improving environmental health. Many of the existing principal urban designers have undervalued the significance of the natural/biological world and environment as a whole (Attenborough, 2019). Implementing blue-green infrastructure (e.g., stormwater management, constructed water bodies, permeable pavements, bioswales, green roofs, and domestic garden, among others.), urban tree canopy, and urban agricultural opportunities in the city environment would reconnect nature (Rice, 2020), which consequently improves long-term human health and societal well-being. In view of future emergencies, it should be encouraged that both government and private sectors' future projects on infrastructure development should be implemented away from urban regions for managing urban-rural migration.

5. Conclusions

This catastrophic lockdown of industrial production and transportation systems could be an unconventional mechanism of environmental restoration. Every year, about 7.0 million people die due to the penetration of fine particulate matter into deep lungs and cardiovascular systems worldwide (WHO, 2018). However, due to this sudden practice of partial-to-complete lockdown, the emission levels of air pollutants have decreased remarkably. Which further leads to reduce mortality and improve human health in a short temporal span across the world. As we know, both NO_2 and $PM_{2.5}$ are very perilous to human health, and so if any city with higher pollution density may also show a higher reduction of NO_2 and $PM_{2.5}$ levels, then this short-term drop will positively act on human health in terms of reducing the respiratory and other diseases. The latest findings indicated that the lockdown interventions with better air quality during Covid-19 have averted tens of thousands of deaths from air pollution over China and Europe (Giani et al., 2020). Notably in the year 2020, the COVID-19 has caused more than 1.02 million deaths (about 3% death w.r.t. the number of infections) (JHU, 2020; WHO, 2018) as of 2nd October 2020 and this value is significantly lower compared to deaths of 7 million people every year due to air pollution at a global scale (WHO, 2018). This situation has been a silver lining for the global environment, which got a chance to heal itself, but it will not be for a long time. In other words, the level of NO_2 and $PM_{2.5}$ will again increase at the level of business as usual scenarios once the government de-escalates lockdown.

The drastic reduction of human activity has reduced the level of air pollution depending upon the efficacy of lockdown. It suggests that by adhering to sustainable transport plans and policies, air pollution in the urban environment could be minimized to a certain extent. The periodic and temporary lockdown (e.g., odd/even transport scheme) can also be implemented in polluted cities if no other alternatives found appropriate. The Stringency index, Containment and Health index demonstrated that the efficacy of lockdown could be adopted on a city scale at least a day during the weekend to decrease air pollutions without compromising economic progress. The analysis also suggests that the intersection of urban design, health, nature, and environment should be promoted by policy-makers in the city environment to safeguard public health, societal well-being, and clean air ecosystem services. The existing clean air policies have been successful to minimize air pollutions in highly polluted cities. Besides those policies, emerging urban policies (i.e. core services, public spaces, urban design, city-level geospatial data, etc.) could be adopted to build urban resilience against any future pandemics and emergencies.

The outbreak of COVID-19 poses a severe threat to human beings and society. On the other hand, nature was healed itself because of lockdown as almost all human activities are partial or completely closed. In this situation, quantification and assessment of atmospheric pollution is high priority research. Here, we have analyzed atmospheric NO_2 level using the Sentinel–5P satellite data to assess the impact of lockdown efficacies at selected cities in Europe and the USA. The findings suggested that imposed lockdown has improved air quality across the urban areas in 11 selected cities. The $PM_{2.5}$ level was improved, although it may last for a short-term duration. It is seen that the enforced pandemic lockdown has helped the Earth to breathe for a while. Nevertheless, it can be inferred that during poor meteorological conditions, an improvement in air quality could be anticipated if the strict implementation of air quality measures implemented by the policymakers with cohabitation among environment, society, and economic growth.

Declaration of competing interest

The authors declare no conflict of interest.

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CRediT authorship contribution statement

B.R.P. and S.B.: Conceptualization, Investigation, Methodology, Software, Analysis, Writing & editing –original draft. S.P.M.: Conceptualization, Methodology, Software. A.C.P., N.K. and B. M.: Conceptualization, Data support, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2021.103308.

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