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Investigating connections between COVID-19 pandemic, air pollution and community interventions for Pakistan employing geoinformation technologies

Khalid Mehmood [a], Yansong Bao [b, c, **], George P. Petropoulos [d], Roman Abbas [e], Muhammad Mohsin Abrar [f], Saifullah [g], Adnan Mustafa [f], Ahmad Soban [h], Shah Saud [i], Manzoor Ahmad [j], Izhar Hussain [k], Shah Fahad [l, *]

[a] School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, 210044, China
[b] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, CMA Key Laboratory for Aerosol-Cloud-Precipitation, Nanjing University of Information Science & Technology, Nanjing 210044, China
[c] School of Atmospheric Physics, Nanjing University of Information Science & Technology, Nanjing 210044, China
[d] Department of Geography, Harokopio University of Athens, El. Venizelou 70, Kallithea, 17671, Athens, Greece
[e] Multan Medical and Dental College, Multan, Pakistan
[f] National Engineering Laboratory for Improving Quality of Arable Land, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, 100081, China
[g] Department of Environmental Health, College of Public Health, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia
[h] Software Engineering Department Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Pakistan
[i] Department of Horticulture, Northeast Agricultural University, Harbin, China
[j] Department of Agriculture, Bacha Khan University Charsadda, 24461, Khyber Pakhtunkhwa, Pakistan
[k] Department of Plant Breeding & Genetics, University of Haripur, Khyber Pakhtunkhwa, Pakistan
[l] Department of Agronomy, University of Haripur, Khyber Pakhtunkhwa, Pakistan

HIGHLIGHTS

- Geoinformation technologies to analyze COVID19 spread and impacts for Pakistan.
- Explore relationships between COVID19, air pollution & community interventions.
- SIR model was tested without non-pharmacologic interventions (NPI) and with NPI.
- Community interventions impacted the spread of Covid-19 and air quality.
- Pollution events were observed during the strictest lockdown over Pakistan major cities.

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ABSTRACT

Several major cities that witnessed heavy air pollution by particulate matter ($PM_{2.5}$) concentration and nitrogen dioxide (NO_2) have contributed to high rate of infection and severity of the coronavirus disease (COVID-19) pandemic. Owing to the negative impact of COVID-19 on health and economy, it is imperative to predict the pandemic trend of the COVID-19 outbreak. Pakistan is one of the mostly affected countries by recent COVID-19 pandemic in terms of COVID-cases and economic crises. Like other several Asian countries to combat the virus impacts, Pakistan implemented non-pharmacological interventions (NPI), such as national lockdowns. The current study investigates the effect of major interventions across three out of four provinces of Pakistan for the period from the start of the COVID-19 in March 22, 2020 until June 30, 2020, when lockdowns were started to be eased. High-resolution data on NO_2 was recorded from Sentinel-5's Precursor spacecraft with TROPOspheric Monitoring Instrument (Sentinel-5P TROPOMI). Similarly, $PM_{2.5}$ data were collected from sampling sties to investigate possible correlation among these pollutants and COVID-19. In addition, growth and susceptible-infected-recovered (SIR) models utilizing time-series data of COVID-19 from February 26 to December 31, 2020, with- and without NPI

** Corresponding author. Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, CMA Key Laboratory for Aerosol-Cloud-Precipitation, Nanjing University of Information Science & Technology, Nanjing 210044, China.
* Corresponding author.
E-mail addresses: ysbao@nuist.edu.cn (Y. Bao), shah_fahad80@yahoo.com (S. Fahad).

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Sentinel-5
Community interventions
Geoinformation
Pakistan

that encompass the predicted number of infected cases, peak time, impact on the healthcare system and mortality in Pakistan. Maximum mean $PM_{2.5}$ concentration of 108 μgm^{-3} was recorded for Lahore with the range from 51 to 215 $\mu gm^{-3,}$ during strict lockdown (L), condition. This is three times higher than Pak-EPA and US-EPA and four times for WHO guidelines, followed by Peshawar (97.2 and 58 ± 130), Islamabad (83 and 158 ± 58), and Karachi (78 and 50 ± 140). The majority of sampling sites in Lahore showed NO_2 levels higher than 8.75E-5 (mol/m^2) in 2020 compared to 2019 during "L" period. The susceptible-infected-recovered (SIR) model depicted a strong correlation (r) between the predicted and reported cases for Punjab ($r = 0.79$), Sindh ($r = 0.91$), Khyber Pakhtunkhwa (KPK) ($r = 94$) and Islamabad ($r = 0.85$). Findings showed that major NPI and lockdowns especially have had a large effect on minimizing transmission. Continued community intervention should be undertaken to keep transmission of SARS-CoV-2 under control in cities where higher incidence of COVID-19 cases until the vaccine is available. This study provides a methodological framework that if adopted can assist epidemiologist and policy makers to be well-prepared in advance in cities where $PM_{2.5}$ concentration and NO_2 levels are already high in order to minimize the potential risk of further spread of COVID-19 cases.

1. Introduction

Coronavirus Disease 2019 (COVID-19) outbreak emerged in Wuhan, China, (Huang et al., 2020; Zeng et al., 2020), and spread globally within a short period of time and was declared as a pandemic by the World Health Organization (WHO) on March 11, 2020. On February 11, 2020, WHO named the novel disease as Corona Virus Disease 2019 (COVID-19) and it is the fifth pandemic occurring in the recent times globally since the Spanish Flu pandemic back in 1918. COVID-19 spread from China to other countries by human-human transmission and mainly attacks in the lungs of human (L. Liu et al., 2020; Waris et al., 2020). During the past two decades, Coronavirus family has created different spells of pandemic conditions, such as Severe Acute Respiratory Syndrome (SARS) in 2003 and Middle East Respiratory Syndrome Corona Virus (MERSCoV) in 2012 (Cui et al., 2003; Ramdan, 2019; SanJuan-Reyes and Islas-Flores, 2021\; Zhong et al., 2003).

A great deal of literature reveal that atmospheric fine particulate matter composition especially, with diameters of 2.5 μm ($PM_{2.5}$) is associated with several antagonistic health effects through inhalation pathway as can easily penetrate in the human lungs and interact with lung cells to cause serious respiratory diseases (L. Liu et al., 2020; Perrone et al., 2013). $PM_{2.5}$ is composed of an inert carbonaceous core coated with organic chemicals, metals, sulfate, nitrate, with possible adsorbed additional organic pollutants mainly viruses, bacteria, and toxic heavy metals on its surface, which might increase its toxicity levels (Feng et al., 2016; Mehmood et al., 2018; K. Mehmood et al., 2020a; 2020b; Khalid Mehmood et al., 2020). Recently, (WHO (2020) reported that approximately seven million deaths every year due to $PM_{2.5}$ pollution. These fine particles can directly transfer into the respiratory system where these are deposited in the lungs contributing to the severe diseases including chronic obstructive pulmonary disease and stroke (Gu et al., 2017; World Health Organisation, 2018). Numerous medical conditions such as cardiovascular disorders, lung cancer, and respiratory ailments are caused by particulate pollution and it could be fatal in immunocompromised persons. Hence it is expected that the population already exposed to high levels of particle pollution could be at high risk of developing a COVID-19 infection as compared to those experiencing good air quality. According to WHO, individuals suffering from chronic respiratory diseases like asthma and those immune compromised due to cancer, etc., are more vulnerable to COVID-19 infection (Conticini et al., 2020; WHO, 2020). A strong correlation between particulate matter ($PM_{2.5}$) and respiratory diseases including severe acute respiratory syndrome−coronavirus 2 has been generally confirmed over the years by several studies (Horne et al., 2018; Kelly and Fussell, 2011; K. Mehmood et al., 2020b; Mehmood et al., 2018; Sánchez-Triana et al., 2014; Xu et al., 2016).

For example, in China, Zhu et al. (2020) found a significant association between COVID-19 infection and $PM_{2.5}$ infections over 120 cities. Similarly, Wu and McGoogan (2020) have suggested that an increase of 1 μgm^{-3} of $PM_{2.5}$ corresponds to a 15% increase in COVID-19 mortality. Certain developments in mechanisms associated with airway complications due to $PM_{2.5}$ and PM_{10} thought to be an epigenetic variation of genes by incineration of particle pollutants and how multiplicity in genes participated in antioxidant routes and airway infection can transform responses to air pollution exposures (Cui et al., 2003; Naeem et al., 2021; Shahbaz et al., 2019; Xie et al., 2018). Primary areas of concern for COVID-19 are associated with large scale transmissions, infection, reoccurrence, a substantial number of deaths, multidimensional effects in susceptible groups, and healthcare 'providers'. Toxicological and epidemiological studies endure to support a relationship between urban particle pollution (due to combustion of fossil fuels products or other anthropogenic sources), and various diseases such as airway hyper-responsiveness and airway inflammation causing an increase in the incidence or severity of respiratory diseases (Bilen et al., 2019; Peters et al., 1999; Turan, 2019).

Similar to SARS-CoV and influenza viruses, SARS-CoV-2 was observable in aerosols for up to 3 h, in liquid and solid phases (van Doremalen et al., 2020). Recently, it is found that SARS-CoV-2 RNA can exist on outdoor particulate matter, and noticed that, in environments of atmospheric stability and high concentrations of particulate matter, SARS-CoV-2 could develop clusters with outdoor particulate matter and thus by reducing their diffusion coefficient increase the endurance of the virus in the atmosphere (Setti et al., 2020a). In another study (Setti et al., 2020b), has confirmed the airborne transfer factor likely to be the interpreting anomalous COVID-19 pandemic in northern Italy, that is distinguished by high particulate matter load especially $PM_{2.5}$ concentrations. Consequently, such results suggest that COVID-19 transmission is possible influenced by airborne $PM_{2.5}$.

High nitrogen dioxide (NO_2) level is also responsible for respiratory deaths and contributes to generate certain toxic secondary pollutants include ozone and nitric acid (Aslam et al., 2020; Hoek et al., 2013; Khoder, 2002). WHO has identified that health hazards may exist due to the occurrence of NO_2 or its secondary products (World Health Organization, 2003). Recently, Ogen (2020) observed that mortality cases were associated with high levels NO_2 in four European countries could be a major contributor to the high COVID-19 mortality rates observed in these regions. Hence, the

WHO recognizes the health issue emerging from NO_2 and proposes that the world should be a safeguard from exposure to this contaminant.

In recent decades, Pakistan has witnessed fast industrial growth, which has positively improved the living standard of the community, and it is also obvious from the escalating vehicular plying on roads. However, the nation has paid an enormous cost for this progress in terms of deteriorating air quality. According to the World Air (2018), two cities (Lahore and Faisalabad) are among the world's top 30 most polluted cities, and 1,11000 deaths due to poor air quality in Pakistan are recorded every year in the country (Lelieveld et al., 2015). It is worth mentioning that Pakistan ranked the second most polluted country after Bangladesh in the world with an annual $PM_{2.5}$ average of 65.8 μg/m^3 (Quality, 2019).

Timely identification of disease episodes is critical for effective infectious control strategy. Recently, spatial data on COVID-19 are gathered but usually not employed in general infectious disease inspection Latest technologically advanced approaches such as geoinformation allows to robustly and quantitatively estimate and, predict its further development and offer an opportunity to examine and illustrate the condition of early detection of disease outbreaks (Meng, 2017). The thematic perspective of COVID-19 and $PM_{2.5}$ pollution demands analysis which utilize an interdisciplinary approach. Geoinformation is one of the key disciplines that purport to offer a synthetic strategy to the interplay between biophysical and human factors s such as community interventions. Epidemiology analysis is applied to explain the distribution of disease in the population and to identify the causes of these diseases. On the other hand, stochastic modeling approach is helpful to forecast the probability and intensity of disease spread. It also offers valuable evidence for decisive the nature and severity of disease intervention. With the information of modeling studies, the resources can be preoccupied to mitigate the risk of infection for better future outcomes.

Based on susceptible-infected-recovered (SIR) model results, Choi and Pak (2003) predicted the SARS positive cases and fatalities in Canada and estimated infectious cases developed were around 1.5 to 2 per infection every five days and 30% of infected patients died within 14 days. Zhao et al. (2020) utilized the exponential model to estimate the variations in recorded rate and predicted the intrinsic growth for SARS and MARS diseases. According to the study findings, the basic reproductive number (R_o) ranged from 2.24 to 3.58. Wu et al. (2020) developed an extended SEIR model to predict the transmission of COVID-19 both within and outside of China. However, these findings assumed that the exposed communities were not infectious, which may be not appropriate in the case of COVID-19. Furthermore, these studies did not take into account the phase-adjusted preventive steps and time-varying factors, which may affect the forecast results.

On January 7, 2021, global confirmed positive COVID-19 number of cases was 85,929,428, with 1,876,1000, deaths recorded from >218 countries worldwide. In Pakistan, the outbreak of COVID-19 started in Karachi city where the first COVID-19 case was reported on February 26, 2020. On January 7 2021 Pakistan reported 10,558 fatalities and a total 497,510 confirmed COVID-19 cases, of which Karachi, Lahore, and Peshawar represented 7.12%, 5.37%, and 9.69% respectively. It is worth mentioning that the severity of COVID-19 spread was higher in big cities than in small towns and villages. It is possible that long-term chronic exposure to $PM_{2.5}$ particles in Lahore, Karachi, Peshawar, and Islamabad metropolitan cities might have played a significant role in the spread of COVID-19 because long term exposure to high levels of $PM_{2.5}$ is directly related to the decline in lung function and initiation of respiratory problems such as shortness of breath, cough, and pain on deep stimulus (Seposo et al., 2020).

Recently, Sipra et al. (2020) assessed the impact of COVID-19 on the hourly concentrations of $PM_{2.5}$ using multifractal analysis in Lahore and Karachi, Pakistan. Similarly, Ali et al. (2020) focused on using ground-based $PM_{2.5}$ pollution satellite observations (AOD) during the lockdown period (23 March to April 15, 2020) as compared to before lockdown. However, these studies did not take into account the NO_2 which has a significant role in the spread of COVID-19 and predictions model include SIR model. Looking at these factors, the present study highlights the added value of geospatial technologies in the interpretation of community interventions, $PM_{2.5}$ pollution and epidemiological analysis simultaneously to understand the COVID-19 pattern using as a case study Pakistan. The proposed here approach is also full reproducible in other locations to globally provided that data required for its implementation is readily available.

In purview of the above, the present study investigates the air quality and COVID-19 distribution during pre-lockdown (PL), lockdown (L), relaxation period (RP) and smart lockdown (SL) in major cities (Lahore, Karachi, Peshawar, and Islamabad) of Pakistan using $PM_{2.5}$ concentration data and NO_2 retrieved from Sentinel-5 Precursor spacecraft with TROPOspheric Monitoring Instrument (Sentinel-5P TROPOMI). A SIR model and growth model over Punjab, Sindh, Khyber Pakhtunkhwa (KPK), and Islamabad were employed to cover the effects of different epidemic prevention measures and the health care system.

2. Material and methods

2.1. Experimental set up

The present study was conducted to investigate the changes in $PM_{2.5}$ concentration from a geospatial perspective starting from January 1, 2020, to June 30, 2020 (various phases of "L" in response of COVID-19) and determine the association between pollutants and COVID-19 cases. We have selected $PM_{2.5}$ and NO_2 pollutants because of their contribution in causing several respiratory health effects and thus could play a key role in increase of COVID-19 cases. According to the official COVID-19 stat, the maximum numbers of COVID-19 positive cases for Karachi, Lahore, and Peshawar (Fig. 1). The COVID positive cases data are obtained through public health department announcements and are directly recorded by public and anonymous patient data. Therefore, an ethical endorsement is not mandatory.

World air quality report (2019), ranked Pakistan second after India's which is the most polluted country in the world in terms of dangerous airborne $PM_{2.5}$ particles (IQAir, 2019). The majority of the cities with high levels of $PM_{2.5}$ concentrations were located in the Punjab part of Pakistan. Lahore is the second-largest city of Pakistan and the capital of Punjab province. The 2017 Census data indicate that Lahore has urban agglomeration with a population of 11.13 million showing an annual growth rate of 3.72% and a density of 6300 individuals/km^2 (Pakistan Bureau of Statistics, 2017). Lahore lies between geo-coordinates 31° 32′ 59″ N and 74°20′37″ E with a geographical area of with 1772 km^2. In a recently release IQAir (2019) World Air Quality report, Lahore ranked "second" among the world's most polluted cities with high $PM_{2.5}$ (89.5 μgm^{-3}) concentration compared to the permissible limit of 35 μgm^{-3} (for 24 h) (IQAir, 2019).

Karachi is the largest city in Pakistan and the capital of Sindh province. Karachi has urban mass with a population of 14.91 million showing an annual growth rate of 2.24% and a density of 24000 individuals/km^2 (Pakistan Bureau of Statistics, 2017). Karachi is situated (24° 51′ 36″ N and 67°0′36″ E) at the southern coast of the Arabian Sea with a geographical area of 3780 km^2. According to

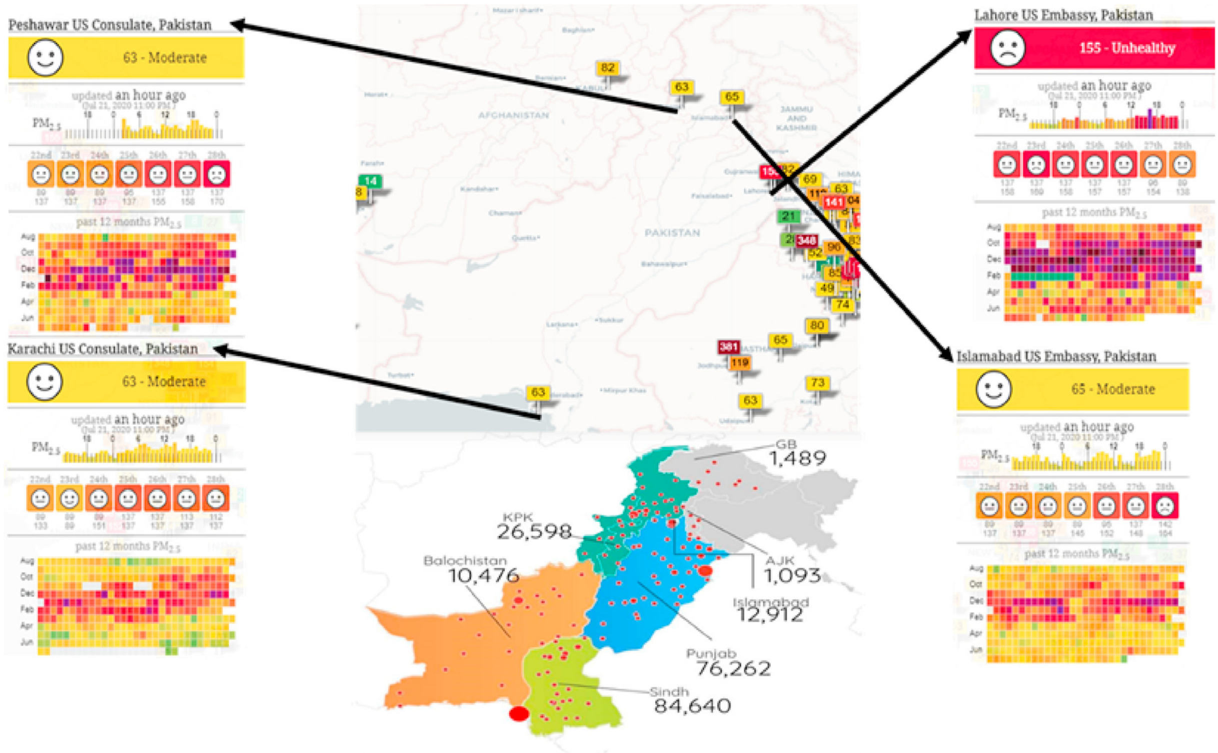

Fig. 1. Locations of $PM_{2.5}$ concentrations data sites at Lahore, Karachi, Peshawar and Islamabad US consulates offices and COVID-19 cases distributions in Pakistan February 26 to June 30, 2020 (sources http://covid.gov.pk/stats/pakistan; Pakistan air quality monitoring US-EPA https://aqicn.org/).

IQAir (2019), Karachi ranked 73rd among the world's most polluted cities, with 40.2 μgm^{-3} $PM_{2.5}$ concentration.

Peshawar is the sixth-largest city and capital of Khyber Pakhtunkhwa province. The total population of 1.97 million showing an annual growth rate of 3.28% and a density of 9200 individuals km^{-2}. Peshawar covers geo-coordinates 34° 01′ N and 71°35′ E with a geographical area of 215 km^2 close to broader with Afghanistan. Peshawar ranked 37 among the world's most polluted cities with high $PM_{2.5}$ (63.9 μgm^{-3}).

Islamabad is the ninth biggest city with 3.1 million population and the capital city of Pakistan (Pakistan Bureau of Statistics, 2017). Islamabad is located at 33° 32′ 35″ N and 73°03′50″ E with 220 km^2 and its enveloping population density of 2089 individuals/km^2 with annual growth of 3.11% (Pakistan Bureau of Statistics, 2017). Regarding $PM_{2.5}$ pollution, Islamabad was ranked at 14 with 35.2 μgm^{-3} $PM_{2.5}$ concentrations and touted as a clean city of the world (IQAir, 2019), and therefore was included in investigation to compare polluted cities with a clean city. Such comparison would provide a real picture of the association between $PM_{2.5}$ levels and severity of COVID-19.

2.2. Datasets & tools

TROPOMI onboard Sentinel-5P was launched on October 13, 2017, in collaboration with Netherlands Space Office (NSO) and European Space Agency (ESA) dedicated to trace gases and climate. This sensor offers daily high resolution (7 × 3.5 km) that is 13 times efficient than the Ozone monitoring instrument. The Sentinel-5P processes ultraviolet earthshine radiances at high spectral. In this study, TROPOMI and NO_2 column datasets were used for the lockdown period and compared with last year from March 22 to May 30, 2019, and March to 22 to 30.

The $PM_{2.5}$ data were collected from the US consulates office at Lahore, Karachi, Peshawar, and Islamabad (Fig. 1). The $PM_{2.5}$ concentration data are available only for these cities. Therefore, we were selected three provinces data for COVID-19 cases. The COVID-19 data for positive cases were retrieved from the Government of Pakistan Official dashboard control by the National Institute of Health (NIH) Islamabad (http://www.nih.org.pk/; Pakistan; http://covid.gov.pk/) (Figure 1). The NO_2 data were retrieved from the European Space Agency (https://apps.sentinel-hub.com/).

2.2.1. SIR and growth models

The standard SIR epidemiological compartmental model is composed of three modules: susceptible, infected, and removed or recovered, which including recovery and mortality. The positive cases indicate the actual confirmed cases; the removed cases state to the improved and expiry cases. Fig. 2 shows the schematic architecture of different compartments of the SIR model. Movement between the compartments is a function of contact rate (c) and transmissibility from susceptible to infected and duration of infectiousness, which determines the movement from infectious to recovered.

The reproduction number (R0) represents the transmissibility of a COVID-19 distribution under no control, indicating the mean number of new infections produced from a single infected person (Imai et al., 2020). COVID-19 is probably to weakening and ultimately disappear if $R0 \leq 1$. To estimate trends and peak of COVID-19 under different community interventions implemented by the government, we used SIR model with a time-varying transmission and contact rates (Song et al., 2020). Table 1 shows the values of different parameters with a brief explanation that is being applied in the SIR model. The model composed of a set of non-linear differential equations (1)–(6), as shown below

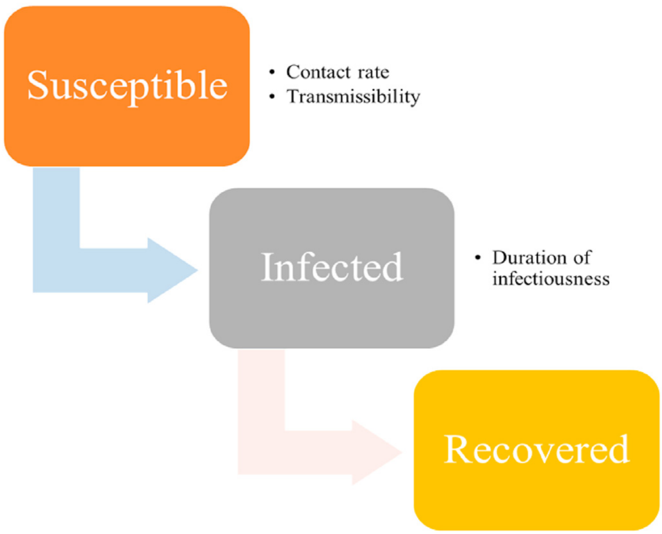

Fig. 2. Schematic diagram of susceptibility infected recovered (SIR) model.

$$\frac{dS}{dt} = -\beta S(t)I(t) \quad (1)$$

where "t" denotes the time (in a day), β(t) is the infection rate that represents the number of individuals contracting infection per unit time. The factor γ(t) is the rate at which infected persons are either recovered or expired. The total number of populations is the sum of the three groups of populations i.e.

$$\frac{dI}{dt} = \beta S(t)I(t) - \gamma I(t) \quad (2)$$

$$\frac{dR}{dt} = \gamma I(t) \quad (3)$$

$$S(t) + I(t) + R(t) = N \quad (4)$$

Herein it was adopted the model proposed by Zhong et al. (2020). It was taken from the total population of each province (Punjab, Sindh, Khyber Pakhtunkhwa and the capital Islamabad of Pakistan) as susceptible. However, several community interventions implemented, which include "L", "RP" and "SL" wearing the mask, washing hands, and social distancing, reduced the size of the susceptible population. However, still, a large population remains vulnerable to COVID19 infection. This study assumed that the large population subject to caught COVID-19 infections. So, one can ignore the population of COVID-19 infection cases. It can streamline the SIR model into an isolated version for execution to the COVID-19 pandemic as the data are available daily. The most appropriate method is finite difference taking for Equations (5) and (6):

$$\beta(t) = I(t + \Delta t) - R(t) \,/\, I(t)\Delta t \quad (5)$$

$$\gamma(t) = R(t + \Delta t) - R(t) \,/\, I(t)\Delta t \quad (6)$$

where Δt indicates is the interval for integration and the change in the infected individuals. In contrast, the second parameter of the model γ(t) is calculated from the difference of recoveries.

$$Needing\ hospitlization = Infected\ cases \times 13.8\% \quad (7)$$

$$Needing\ ICU = Infected\ cases \times 4.70\% \quad (8)$$

$$Mortality = Infected\ cases \times X(Punjab, Sindh,\ KPK,\ Islamabad)\% \quad (9)$$

An exponential growth model was employed to observe the instantaneous changes in COVID-19 cases started from February 26 to June 30, 2020) concerning different community interventions in the studied provinces of Pakistan in Equation (10).

$$y(t) = a \times \exp(bx) + y_0 \quad (10)$$

where a = intercept b = rate of growth and y_t = value at time "t" y_0 = value at time "t = 0″

Similar to previous studies, growth model was used to observe the trend of COVID-19 cases in different provinces of Pakistan and SIR model to predict the number of cases and estimate capacity of health care system in Pakistan (Fang et al., 2020; Roosa et al., 2020).

2.2.2. Air quality assessment

To explain urban air quality of Lahore, Karachi, Peshawar, and Islamabad metropolitan cities, this study considered air quality index (AQI) according to US EPA (2012a, 2012b) classification of air quality standards, which is calculated as follows:

Table 1
Descriptions and values of parameters used in the SIR model.

	Parameters	Symbol	Values	Description
1	Contact rate	β	13.4	The U.S. contact rate (at baseline) might be as low as Germany's (7.95) or as high as Italy's (19.77) but is unlikely to be much different. In this study we have utilized with NPI(4) and without NPI(13.4)
2	Removal rate	γ		Recoveries per person per day
3	Basic Reproduction number	R0		The Reproduction Number is the product of Contact Rate X Transmissibility X Duration of Infection. Thus it can be changed by changing any of those factors.
4	Contacts per infection	β/γ	2%	By comparison, the intrinsic transmissibility of 2009 influenza was estimated at 1.57% (SD 0.41).
5	Duration of infectiousness	d	10	Contact tracing data from 10 early cases in China showed the mean serial interval (time between successive cases) was 7.5 days with a SD of 3.4 days. A more recent estimate among 468 cases was 3.96 days with a 4.75 day SD.
6	% Needing hospitalization		13.8%	Severity of illness with COVID-19 is positively associated with age and the proportion of the population over 65 is 11.9% in China vs 15.8% in the U.S.
7	% Needing ICU care		4.7%	
8	Mortality rate		Punjab (2.31%), Sindh (1.62%), KPK (3.57%) and Islamabad (0.99%)	As of 06/30/20, the average daily mortality rate is adopted according to number COVID-19 cases and total deaths in Punjab (2.31%), Sindh (1.62%), KPK (3.57%) and Islamabad (0.99%).

$$AQI = \left[(PM2.5obs(24hours) - PMmin) \times \frac{(AQImax - AQImin)}{PMmax - PMmin}\right] + AQImin \quad (11)$$

Where, $PM_{2.5}$ represents daily mean values of respectively, particle matter in size 2.5 µm, present in the urban air. Based on the AQI for air quality is classified in eight classes from very good to very critical (Table 2).

2.2.3. Correlation analysis

The descriptive metrics was conducted using for all the acquired data in the analysis. The study applied correlation analysis (r) to see the relationship between $PM_{2.5}$ and COVID-19 cases in various cities of Pakistan.

$$r_{xy} = \frac{cov(x, y)}{\sqrt{var(x)}.\sqrt{var(y)}} \quad (12)$$

Where cov (x, y) is the sample covariance of x and y; var(x) is the sample variance of x; and var(y) is the sample variance of y.

3. Results and discussion

3.1. Air quality studying during community interventions

To understand the effectiveness of community interventions (PL, L, RP, and SL) on the air quality of Lahore, Karachi, Islamabad, and Peshawar, 24 h mean concentrations of $PM_{2.5}$ were compared with Pak-EPA, US-EPA and WHO guidelines (Table 3). During "PL" (started from January 1 to March 21, 2020) maximum mean $PM_{2.5}$ concentration (176 μgm^{-3}) was recorded for Lahore with the range from 21 to 375 μgm^{-3}, which is five times higher than Pak-EPA and US-EPA and seven times than WHO guidelines followed by Peshawar (148.9 and 62 ± 425), Karachi (142.5 and 81 ± 213), and Islamabad (131.7 and 58 ± 236). Fig. 3 shows the AQI for Lahore, Karachi, Peshawar, and Islamabad starting from February, 26 to June 30, 2020. The mean AQI value was found 254.19 reflecting "very unhealthy" air for all types of age groups, and everyone begun to expose unhealthy air quality before the "L" intervention (Fig. 3). This higher $PM_{2.5}$ concentration in Lahore could be associated with the combustion of vehicles, solid waste burning, smoke from brick kilns emissions from a big number of industrial units. Strict "L" intervention was started from March 22 to May 9, 2020, in Lahore and Islamabad, while in Peshawar and Karachi it was implemented from April 2 to May 9, 2020, and March 22 to May, 30 respectively and all educational institutes, businesses, public transport, and commercial centers remained closed during these periods Similar to PL, maximum mean $PM_{2.5}$ concentration of 108 μgm^{-3} was recorded for Lahore with the range from 51 to 215 $\mu gm^{-3,}$ which is three times higher than Pak-EPA and US-EPA and four times for WHO guidelines, followed by Peshawar (97.2 and 58 ± 130), Islamabad (83 and 158 ± 58), and Karachi (78 and 50 ± 140). Interestingly the $PM_{2.5}$ concentrations recorded during strict "L" intervention were quite lower than for PL intervention. Unlike the rest of the world, poor implementation of community interventions in Pakistan contributed to higher levels of $PM_{2.5}$ concentration in these megacities. This study finding corroborate those of Faridi et al. (2020) indicating upsurge in the concentrations of PM2.5 owing to an increase in the usage of private cars during the lockdown periods in Tehran.

Karachi's higher $PM_{2.5}$ concentrations could be attributed to rapid growth in population and commercial activities, while in Peshawar the major source of $PM_{2.5}$ particles was brick kilns that were found operating 24 h around the city. Due to the crumbling economy of Pakistan, the government of Pakistan decided to ease down the "L" starting from May 9 in Lahore, Peshawar, Islamabad, with strict SOPs, while due to a higher rate of COVID-19 cases in Karachi, "L" intervention was stretched to May 30. Unfortunately, from May, 10 to June 17, 2020, designated here as "RP", the number of COVID-19 cases started to increase rapidly that forced the government to re-implement "SL" to handle the situation.

Pearson's correlation (r) for $PM_{2.5}$ concentration and COVID-19 cases from February, 26 to June 30, 2020, indicated poor relationship. Maximum correlation was recorded for Peshawar ($r = 0.36$) and Islamabad ($r = 0.34$) followed by week relation for Lahore ($r = 0.22$) and Karachi ($r = -0.35$). The weak relationship could be ascribed mainly to two reasons. Firstly, $PM_{2.5}$ concentration data were collected from a single monitoring station in each studied city, and secondly, data for city-level for COVID-19 cases was not accessible. So, a correlation between city-level $PM_{2.5}$ concentration and province-level COVID-19 cases was applied. Additionally, it was assumed that all the cases were local and the imported COVID-19 cases were negligible. Overall, this trend demands that there is a certain relationship between $PM_{2.5}$ and COVID-19 cases in the local conditions where higher levels of $PM_{2.5}$ concentration were observed, especially in Lahore.

3.2. Spatial distribution of NO_2

Fig. 4 shows the spatial distribution of tropospheric NO_2 over the Lahore, Karachi, Peshawar, and Islamabad during strict community intervention in 2020 and compared with 2019 during the "L" period. It can be seen that there is no significant improvement in air quality in terms of daily tropospheric NO_2 in Lahore and Karachi compared to 2019. The majority of the sites showed NO_2 levels more than 8.75E-5 (mol/m^2) in Lahore during 2020 but lower compared to 2019, especially northwest and south Lahore due to the closure of oil-based power plants while in Karachi, few sites

Table 2
Air quality index categorization for $PM_{2.5}$ polluants (μgm^{-3}).

AQI	Concentration divisions of $PM_{2.5}$ polluants (μgm^{-3})	*Risk analysis (AQI)
0–50	0.0–12	Good
50–100	12.1–35.4	Marginal (moderate)
101–150	35.5–55.4	Unhealthy for sensitive group
151–200	55.5–150.4	Poor (unhealthy)
201–300	150.5–250.4	Very poor (very unhealthy)
301–400	250.5–350.4	Hazardous
401–500	350.5–500	Very hazardous
>500	>500	Very critical

US EPA (2012a, 2012b).

Table 3
Descriptive analysis of $PM_{2.5}$ concentrations (24 h) for Lahore, Karachi, Islamabad and Karachi during community interventions.

Community interventions	Lahore	Karachi	Peshawar	Islamabad
Pre-lock down (PL)	January 1 to March 22, 2020	January 1 to March 22, 2020	January 1 to April 2, 2020	January 1 to March 22, 2020
Maximum	375.0	213.0	425.0	236.0
Minimum	31.0	81.0	62.0	58.0
Average	176.0	142.5	148.9	131.7
Standard deviation	84.7	31.8	52.6	34.9
Lock down (L)	March 22 to May 9, 2020	March 22 to May 30	April 2 to May 9, 2020	March 22 to May 9, 2020
Maximum	215.0	140.0	130.0	119.0
Minimum	51.0	50.0	58.0	58.0
Average	108.9	78.0	97.2	83.0
Standard deviation	33.5	16.2	19.0	12.5
Relaxation period (RL)	May 10 to June 16, 2020	June 1 to June 17, 2020	May 10 to June 16, 2020	May 10 to June 17, 2020
Maximum	199.0	98.0	137.0	105.0
Minimum	92.0	59.0	58.0	65.0
Average	133.5	77.7	101.7	82.6
Standard deviation	27.5	11.0	19.1	9.4
Smart lockdown (SL)	June 17 to June 30	June 18 to June 30	June 17 to June 30	June 18 to June 30
Maximum	157.0	84.0	163.0	146.0
Minimum	88.0	49.0	106.0	82.0
Average	134.9	65.3	126.9	103.8
Standard deviation	21.0	11.4	47.2	16.3

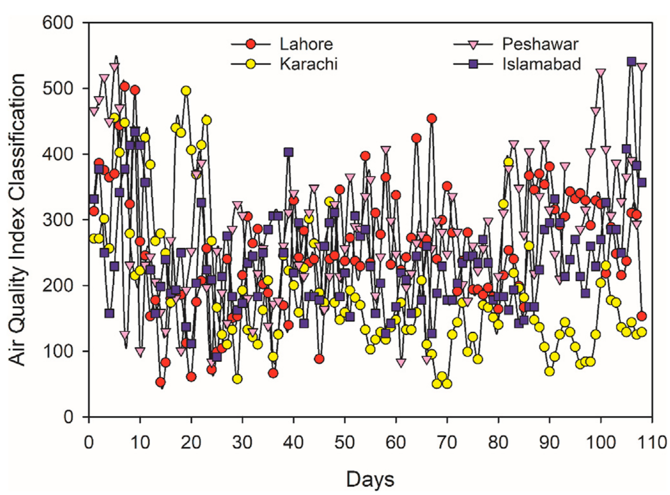

Fig. 3. Air quality index during March 15 to June 30, 2020 in Lahore, Karachi, Islamabad and Peshawar.

were found higher NO_2 value especially Korangi, Landhi industrial and fertilizer and cement plant at Bin Qasim port. Contrary to Lahore and Karachi, NO_2 levels were lower in Peshawar and Islamabad except few sites compared to 2019 (Fig. 4). In case of Islamabad, and Peshawar, effective implementation during SL, led to substantial reduction in NO_2. The current study shows good agreement with Aslam et al. (2020) who reported significant decrease in concentration of NO_2 in Islamabad. Higher NO_2 values in Lahore could also be attributed to plastic burning and a big network of steel and iron manufacturing factories and brick kilns sporadic around the city (Filonchyk and Peterson, 2020; L et al., 2013; ul-Haq et al., 2014). This situation also implies that the community did not strictly follow the community interventions, which leads to higher NO_2 values, resulting in the maximum COVID-19 cases both in the Lahore and Karachi. Those findings are in line with findings of Ogen (2020) which show that spatial variation of mortality cases associated with high levels NO_2 in four European countries could be a major contributor to the high COVID-19 mortality rates observed in these regions.

3.3. Epidemic development of COVID-19 in Punjab, Sindh, Khyber Pakhtunkhwa, and Islamabad

In Pakistan, the new number of COVID-19 cases has been increasing almost every day since the first case was reported on February 26, till June 30, 2020. Schools, universities, public transport, and business were closed. Over time, various community mitigation efforts have been announced and implemented. The NIH Pakistan data for the cumulative cases and daily counted cases were plotted to examine the increase in the number of cases for 126 days. Fig. 5 illustrates an epidemiological trend of COVID-19, reflects an exponential rise in the number of cases over Punjab, Sindh, Khyber Pakhtunkhwa, and Islamabad since the outbreak started in Pakistan on February 26, 2020 in Sindh (Fig. 5). Uncertainty is still existing that how many will be infected by COVID-19 and when will the epidemic peak occur.

Under the first experiment without non-pharmacologic interventions (NPI), the SIR model for the distribution of COVID-19 in Punjab, Sindh, Khyber Pakhtunkhwa, and Islamabad under the assumptions adopted in model parameters, suggested that the number of infections were peaked on July 15, June 30, June 20 and June 14, 2020, where 2,94,892,855 (Punjab), 5,55,95,538 (Sindh), 528186 (Khyber Pakhtunkhwa), 5,38,06 (Islamabad) and individuals could be probably infected (Fig. 6). The results show the number of hospitalizations, ICU, and mortality cases over Punjab, Sindh, KPK, and Islamabad without NPI. We also superimposed the predicted data with the reported numbers. The proposed model suggests a strong correlation for predicted and reported cases for Punjab ($r = 0.79$), Sindh ($r = 0.91$), Khyber Pakhtunkhwa ($r = 94$) and Islamabad ($r = 0.85$).

However, until June 30, the number of cases is significantly lower than the actual reported cases in Pakistan. A possible reason for this might the large number of unidentified COVID-19 cases, asymptomatic and demographic disease variations. This study was motivated to predict the COVID-19 epidemic over different provinces of Pakistan to assess the number of infections, the peak infection date, the rate of rising infections, and the resolution of the end-point of the pandemic. The modeling factors were modified according to the population and mortality rates of each province of Pakistan (Table 1).

(Bootsma and Ferguson, 2007; Du et al., 2020; Imai et al., 2020; Li et al., 2020; Mossong et al., 2008; Rocklöv et al., 2020; "The

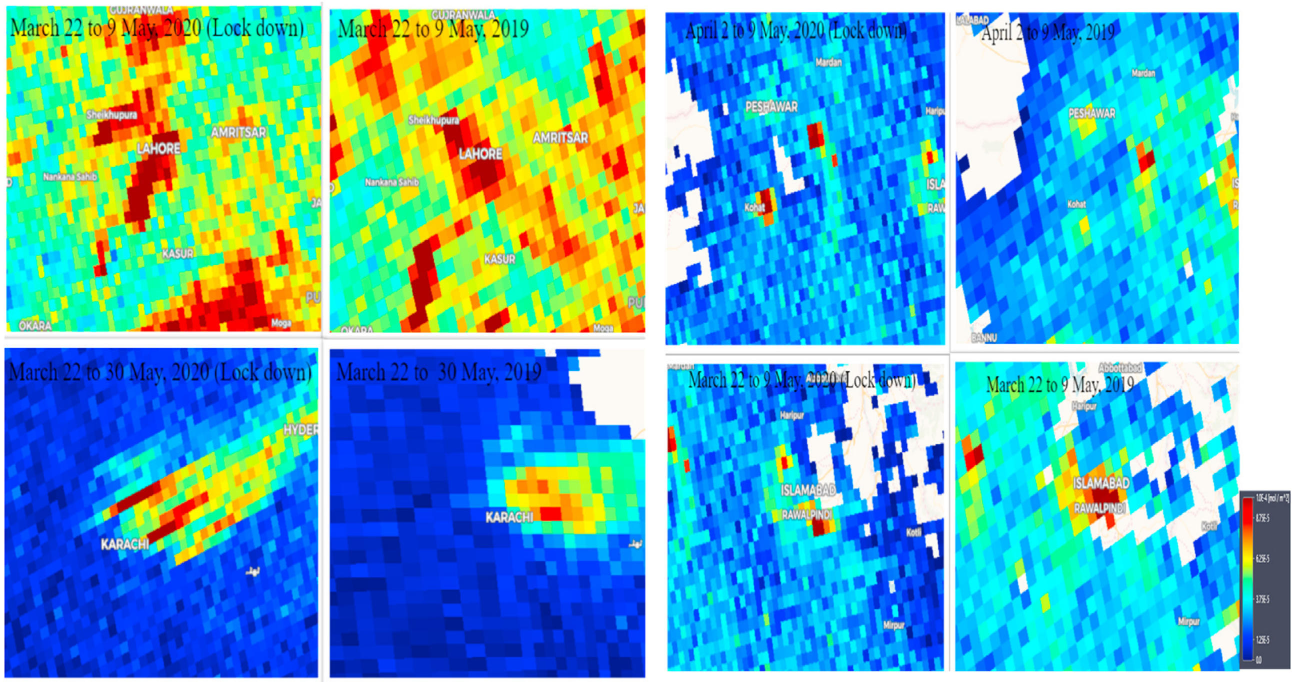

Fig. 4. Comparison of Tropospheric column of NO_2 (Sentinel 5P) over Lahore, Karachi, Peshawar and Islamabad during community interventions in 2020 versus March 22 to May 30, 2019 (http://www.tropomi.eu/data-products/nitrogen-dioxide).

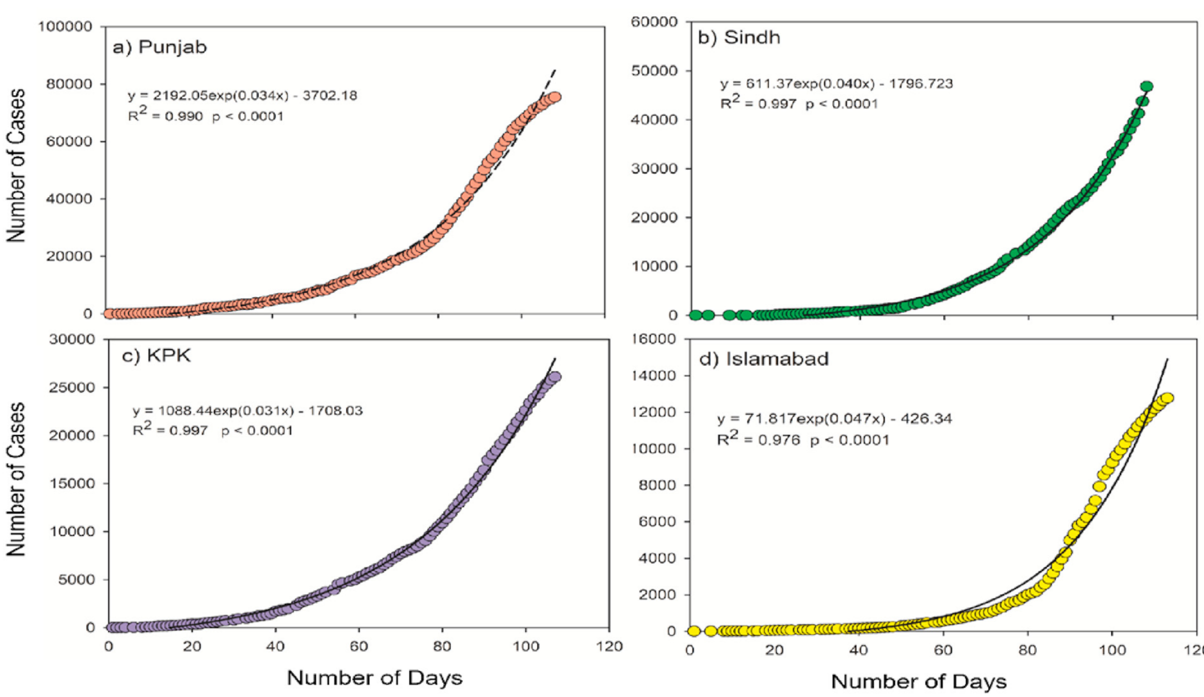

Fig. 5. Exponential growth model in Punjab, Sindh, Khyber Pakhtunkhwa (KPK) and Islamabad. during February 26 to June 30, 2020.

epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19) in China," 2020).

The model simulated the conditions where COVID-19 is distributing in a closed population, without NPI such as social distancing, wearing mask, travel restrictions, and, hand washing, etc. The values of Ro = 2.68, $\beta = 0.68$, and $\gamma = 0.1$ estimated data, which were reasonably close to the actual reported cases in each province and Islamabad (Fig. 6) started from February 26 to June 30, 2020. Furthermore, the trends of the predicted infection and the reported number of infections agree significantly. Previous studies from China have proposed that COVID-19 originally tails an exponential growth trend coupled with rapid increase in the number of infections (Bai et al., 2020; Liu et al., 2020; Wu et al., 2020a).

Under the second experiment, where were adopted NPI

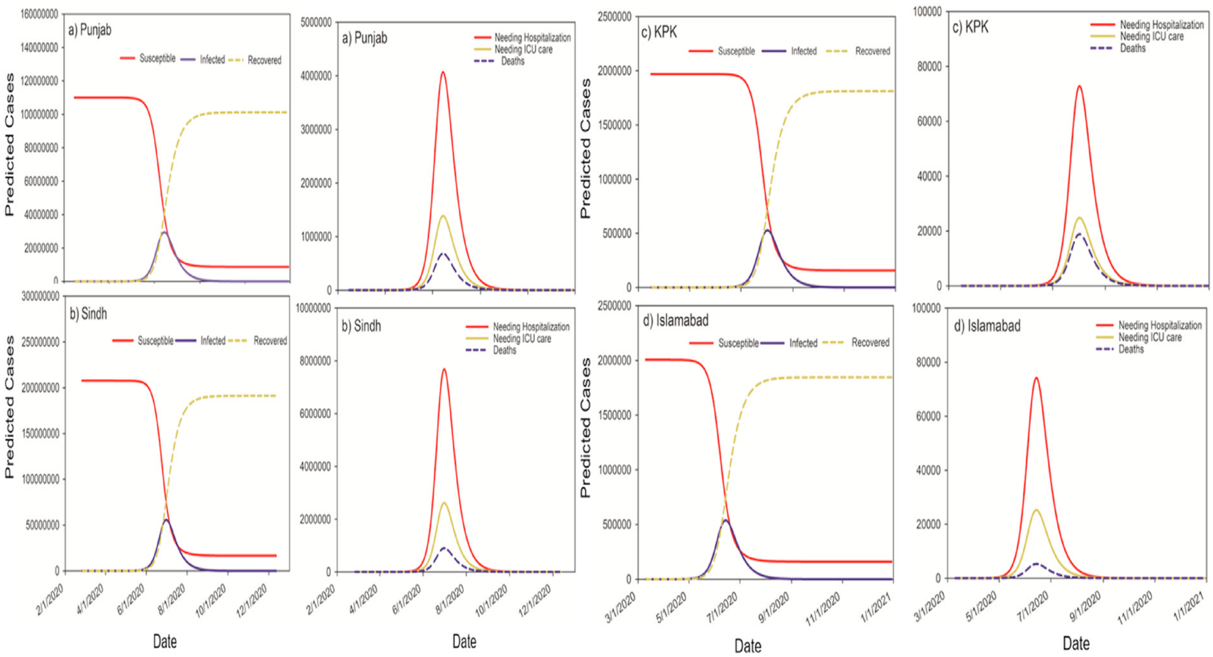

Fig. 6. SIR model (without NPI) health care system predictions and curve evaluation over Punjab, Sindh, KPK and Islamabad.

(assumes an 80% reduction in contact rate "4" started from March 22 to May 2020 with $R_o = 0.8$, $\beta = 0.08$, and $\gamma = 0.1$ values lead to the different trend of infection, recovery, mortality rate and curve evaluation. The SIR model suggested that the number of second infections peak was occurred on September 8, September 19 for Punjab and Sindh respectively, and were happened for Khyber Pakhtunkhwa on August 2, and were occurred at June 14 for Islamabad, where 2,95,01108 (Punjab), 5,57,17,387 (Sindh), 528103 (Khyber Pakhtunkhwa), 5,38,062 (Islamabad) individuals could be probably infected.

Fig. 6 illustrates the number of hospitalizations, ICU, and mortality cases over Punjab, Sindh, KPK, and Islamabad with NPI. Correlating the described data with the model predictions, it can assume that if left unchecked, the disease can distribute at an exponential rate in Pakistan, especially in adjacent communities and heavily populated zones where atmospheric pollution is already affecting a large number of population (K. Mehmood et al., 2020a; Khalid Mehmood et al., 2020). The effect of the COVID-19 response in China in terms of quarantine procedures, social distancing, and isolation of infections is promising for other countries (Anderson et al., 2020).

In the present study, the SIR model was employed to estimate the impact of community intervention measures on the Pakistani COVID-19 pandemic condition. Previously, it was determined that the epidemic of an infectious disease is frequently performed by applying constant factors (Fang et al., 2020; Roosa et al., 2020; Zhao et al., 2020). Li et al. (2020) calculated R_o to be 2.2 among the first 425 patients in Wuhan (Li et al., 2020). Other findings predicted R_o to be 2.68 (Wu et al., 2020b), 3.6–3.8 (Read et al., 2020), and 6.47 (Tang et al., 2020). Y. Liu et al. (2020) observed that the predicted mean Ro for COVID-19 is about 3.28, by studying Ro of COVID-19 in 12 kinds of research (J. Liu et al., 2020). Similarly, Wangping et al. (2020) estimated that the mean of Ro was to be 2.58 and 3.16 in the SIR model and eSIR model in Hunan, which is close to this study under without NPI and higher with NPI experiment. This is due to the estimation of Ro in the SIR model is modified according to the community mitigation measures.

Past studies have suggested that more rigorous government control mechanism policies were linked with a slower increase in the infected population (Chinazzi et al., 2020; Fang et al., 2020). In the present study, compared with NPI in the SIR model (Fig. 7) effective government control policies in Punjab, Sindh, KPK, and Islamabad intensely decreased the number of COVID-19 cases suggesting that adopting government control earlier could have decreased the number of infected cases before peak time.

The results of this experiment indicated that the predicted peak dates are different in different provinces, however, these time periods are close to the maximum number of reported COVID cases in Pakistan. So, this model is relatively reliable and serve as baseline for other studies and for policy makers to prepare well in advance. Furthermore, several mitigation efforts, including the premature detection, tracking, and segregation of individuals with symptoms, home quarantine, traffic limits, and entry or exit screening followed by many other countries, such as China, can well-prevent the extra spread of COVID-19. These efforts are in according to the latest recommendations by the WHO. However, the best operative strategy still needs to be established by further epidemiological investigations and SOPs according the new evolving situation in the affected countries including Pakistan.

The present study implementation has been subject to certain limitations that also need to be acknowledged. In particular, the study does not exclude that a coactive with other dynamics such as meteorological and cultural factors, etc., could occur. In addition, the current study focused on the study of $PM_{2.5}$ and NO_2 only; yet, other multi pollutant analyses are certainly interesting to be investigated as well since those are also warranted.

Regarding models, SIR model is a closed system and simple because it works in stable environment. The incubation period was not taken into this study. Hattaf et al. (2013) suggested if time delay or incubation period is neglected, Ro value in a delayed SIR model would be overestimated. Last, but perhaps not least, based on a limited number of tests performed, the unconfirmed and asymptomatic cases may be overlooked. Some unexpected factors may contribute to this study, such as presence of super-spreaders.

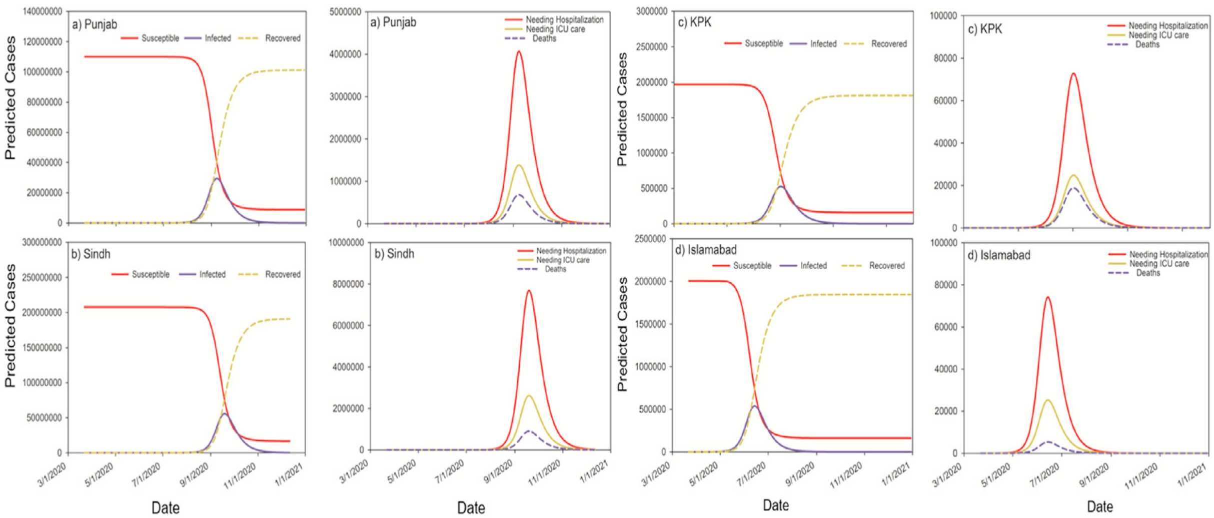

Fig. 7. SIR model (with NPI), health care system predictions and curve evaluation over Punjab, Sindh, KPK and Islamabad.

4. Conclusions & future outlook

To our knowledge for the first time for Pakistan, this study highlights the changes in $PM_{2.5}$ concentrations with community interventions and epidemiological analysis (NPI and non NPI) from a geospatial perspective in Pakistan. Maximum mean $PM_{2.5}$ concentration of 108 μgm^{-3} was recorded for Lahore with the range from 51 to 215 $\mu gm^{-3,}$ which is three times higher than Pak-EPA and US-EPA and four times for WHO guidelines, followed by Peshawar (97.2 and 58 $\pm$ 130), Islamabad (83 and 158 $\pm$ 58), and Karachi (78 and 50 $\pm$ 140).. The mean value for AQI ranged from 214.6 to 280.1 reflecting “very unhealthy” air quality for Lahore, Karachi, Peshawar, and Islamabad during February 26 to June 30. This proposed model SIR model without NPI and NPI have been employed to predict the probable number of positive cases of COVID-19 and overwhelming the health care system in Pakistan till December 2020. The study findings support the argument that use of geoinformation technologies can restructure efforts for future in other highly polluted cities of world with respect to trend and distribution of COVID-19 cases. This type of study offered a good tool when a new emergent situation come across in future and it also provide to define the new step in research and an emergency response to crises when we have short time to predict it. The approach presented in this study can provide important assistance to epidemiologists and environmentalists to understand the changing patterns spatially of different COVID-19 strains under diverse environments. Future work can focus on exploring the added value of meteorological and other toxic air pollutant data in this line of investigation linked to COVID-19 spatial distribution trends.

Author contributions

For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used “Conceptualization, Khalid Mehmood, Yansong Bao and Shah Fahad methodology, Roman Abbas, Saifullah, and Muhammad Mohsin Abrar.,; software, George P. Petropoulos validation, George P. Petropoulos and Muhammad Mohsin Abrar.; formal analysis, Adnan Mustafa, Izhar Hussain and Ahmad Soban, investigation, Khalid Mehmood, resources, Manzoor Ahmad, data curation, Shah Saud,; writing—original draft preparation, Khalid Mehmood; writing—review and editing, Shah Fahad and George P. Petropoulos.

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Availability of data and materials

The datasets generated ($PM_{2.5}$ concentrations, NO_2 and COVID-19 cases data) and/or analysed during the current study are available in the (Pakistan air quality monitoring US-EPA (https://aqicn.org/), National Institute of Health, Pakistan (http://www.nih.org.pk/; http://covid.gov.pk/), European Space Agency (https://apps.sentinel-hub.com/).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ali, S.M., Malik, F., Anjum, M.S., Siddiqui, G.F., Anwar, M.N., Lam, S.S., Nizami, A.S., Khokhar, M.F., 2020. Exploring the linkage between PM2.5 levels and COVID-19 spread and its implications for socio-economic circles. Environ. Res. https://doi.org/10.1016/j.envres.2020.110421.

Anderson, R.M., Heesterbeek, H., Klinkenberg, D., Hollingsworth, T.D., 2020. How will country-based mitigation measures influence the course of the COVID-19 epidemic? Lancet. https://doi.org/10.1016/S0140-6736(20)30567-5.

Aslam, B., Khalil, U., Azam, U., Maqsoom, A., 2020. A correlation study between weather and atmosphere with COVID-19 pandemic in Islamabad, Pakistan. Spat. Inf. Res. https://doi.org/10.1007/s41324-020-00366-2.

Z, L., Ahmad, S.S., Syed, W.A.A., 2013. Temporal variations in nitrogen dioxide concentration due to vehicular emissions in Islamabad capital territory (ICT) & Rawalpindi. Sci. Int. 24, 265−268.
Bai, Y., Yao, L., Wei, T., Tian, F., Jin, D.Y., Chen, L., Wang, M., 2020. Presumed asymptomatic carrier transmission of COVID-19. JAMA, J. Am. Med. Assoc. https://doi.org/10.1001/jama.2020.2565.
Bilen, S., Bilen, M., Turan, V., 2019. Relationships between cement dust emissions and soil properties. Pol. J. Environ. Stud. https://doi.org/10.15244/pjoes/92521.
Bootsma, M.C.J., Ferguson, N.M., 2007. The effect of public health measures on the 1918 influenza pandemic in U.S. cities. Proc. Natl. Acad. Sci. U. S. A. https://doi.org/10.1073/pnas.0611071104.
Chinazzi, M., Davis, J.T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Pastore y Piontti, A., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Elizabeth Halloran, M., Longini, I.M., Vespignani, A., 2020. The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. Science 80−. https://doi.org/10.1126/science.aba9757.
Choi, B.C.K., Pak, A.W.P., 2003. A simple approximate mathematical model to predict the number of severe acute respiratory syndrome cases and deaths. J. Epidemiol. Community Health. https://doi.org/10.1136/jech.57.10.831.
Conticini, E., Frediani, B., Caro, D., 2020. Can atmospheric pollution be considered a co-factor in extremely high level of SARS-CoV-2 lethality in Northern Italy? Environ. Pollut. https://doi.org/10.1016/j.envpol.2020.114465.
Cui, Y., Zhang, Z.-F., Froines, J., Zhao, J., Wang, H., Yu, S.-Z., Detels, R., 2003. Air pollution and case fatality of SARS in the People's Republic of China: an ecologic study. Environ. Heal. https://doi.org/10.1186/1476-069x-2-15.
Du, Z., Xu, X., Wu, Y., Wang, L., Cowling, B.J., Meyers, L.A., 2020. Serial interval of COVID-19 among publicly reported confirmed cases. Emerg. Infect. Dis. https://doi.org/10.3201/EID2606.200357.
Fang, Y., Nie, Y., Penny, M., 2020. Transmission dynamics of the COVID-19 outbreak and effectiveness of government interventions: a data-driven analysis. J. Med. Virol. https://doi.org/10.1002/jmv.25750.
Faridi, S., Yousefian, F., Niazi, S., Ghalhari, M.R., Hassanvand, M.S., Naddafi, K., 2020. Impact of sars-cov-2 on ambient air particulate matter in Tehran. Aerosol Air Qual. Res. https://doi.org/10.4209/aaqr.2020.05.0225.
Feng, S., Gao, D., Liao, F., Zhou, F., Wang, X., 2016. The health effects of ambient PM2.5 and potential mechanisms. Ecotoxicol. Environ. Saf. https://doi.org/10.1016/j.ecoenv.2016.01.030.
Filonchyk, M., Peterson, M., 2020. Air quality changes in shanghai, China, and the surrounding urban agglomeration during the COVID-19 lockdown. J. Geovisualization Spat. Anal. https://doi.org/10.1007/s41651-020-00064-5.
Gu, X. yu, Chu, X., Zeng, X.L., Bao, H.R., Liu, X.J., 2017. Effects of PM2.5 exposure on the Notch signaling pathway and immune imbalance in chronic obstructive pulmonary disease. Environ. Pollut. https://doi.org/10.1016/j.envpol.2017.03.070.
Hattaf, K., Lashari, A.A., Louartassi, Y., Yousfi, N., 2013. A delayed sir epidemic model with general incidence rate. Electron. J. Qual. Theor. Differ. Equ. https://doi.org/10.14232/ejqtde.2013.1.3.
Hoek, G., Krishnan, R.M., Beelen, R., Peters, A., Ostro, B., Brunekreef, B., Kaufman, J.D., 2013. Long-term air pollution exposure and cardio-respiratory mortality: a review. Environ. Heal. A Glob. Access Sci. Source. https://doi.org/10.1186/1476-069X-12-43.
Horne, B.D., Joy, E.A., Hofmann, M.G., Gesteland, P.H., Cannon, J.B., Lefler, J.S., Blagev, D.P., Kent Korgenski, E., Torosyan, N., Hansen, G.I., Kartchner, D., Arden Pope, C., 2018. Short-term elevation of fine particulate matter air pollution and acute lower respiratory infection. Am. J. Respir. Crit. Care Med. https://doi.org/10.1164/rccm.201709-1883OC.
Huang, Z., Huang, J., Gu, Q., Du, P., Liang, H., Dong, Q., 2020. Optimal temperature zone for the dispersal of COVID-19. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.139487.
Imai, N., Cori, A., Dorigatti, I., Baguelin, M., Donnelly, C.A., Riley, S., Ferguson, N.M., 2020. Report 3: Transmissibility of 2019-nCoV. Imp. Coll. London.
IQAir, 2019. World air quality report. 2019 world air qual. For. Rep.
Kelly, F.J., Fussell, J.C., 2011. Air pollution and airway disease. Clin. Exp. Allergy. https://doi.org/10.1111/j.1365-2222.2011.03776.x.
Khoder, M.I., 2002. Atmospheric conversion of sulfur dioxide to particulate sulfate and nitrogen dioxide to particulate nitrate and gaseous nitric acid in an urban area. Chemosphere. https://doi.org/10.1016/S0045-6535(02)00391-0.
Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D., Pozzer, A., 2015. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature. https://doi.org/10.1038/nature15371.
Li, Q., Guan, X., Wu, P., Wang, X., Zhou, L., Tong, Y., Ren, R., Leung, K.S.M., Lau, E.H.Y., Wong, J.Y., Xing, X., Xiang, N., Wu, Y., Li, C., Chen, Q., Li, D., Liu, T., Zhao, J., Liu, M., Tu, W., Chen, C., Jin, L., Yang, R., Wang, Q., Zhou, S., Wang, R., Liu, H., Luo, Y., Liu, Y., Shao, G., Li, H., Tao, Z., Yang, Y., Deng, Z., Liu, B., Ma, Z., Zhang, Y., Shi, G., Lam, T.T.Y., Wu, J.T., Gao, G.F., Cowling, B.J., Yang, B., Leung, G.M., Feng, Z., 2020. Early transmission dynamics in wuhan, China, of novel coronavirus−infected pneumonia. N. Engl. J. Med. https://doi.org/10.1056/nejmoa2001316.
Liu, J., Zhou, J., Yao, J., Zhang, X., Li, L., Xu, X., He, X., Wang, B., Fu, S., Niu, T., Yan, J., Shi, Y., Ren, X., Niu, J., Zhu, W., Li, S., Luo, B., Zhang, K., 2020. Impact of meteorological factors on the COVID-19 transmission: a multi-city study in China. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138513.
Mehmood, K., Ahmad, H.R., Abid, A.A., Guo, P., 2018. A preliminary assessment and control strategy of size segregated pollutants in urban and peri-urban areas of metropolitan Faisalabad, Pakistan. Pakistan J. Anal. Environ. Chem. https://doi.org/10.21743/PJAEC/2018.12.16.
Mehmood, Khalid, Saifullah Iqbal, M., Abrar, M.M., 2020. Can exposure to PM2.5 particles increase the incidence of coronavirus disease 2019 (COVID-19)? Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.140441.
Mehmood, K., Saifullah Abrar, M.M., Iqbal, M., Haider, E., Shoukat, H.M.H., 2020a. Can $PM_{2.5}$ pollution worsen the death rate due to COVID-19 in India and Pakistan? Sci. Total Environ. 742 https://doi.org/10.1016/j.scitotenv.2020.140557.
Mehmood, K., Saifullah Iqbal, M., Rengel, Z., Abrar, M.M., 2020b. Pakistan and India collaboration to improve regional air quality has never been more promising. Integrated Environ. Assess. Manag. https://doi.org/10.1002/ieam.4292.
Meng, Q., 2017. The impacts of fracking on the environment: a total environmental study paradigm. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2016.12.045.
Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., Massari, M., Salmaso, S., Tomba, G.S., Wallinga, J., Heijne, J., Sadkowska-Todys, M., Rosinska, M., Edmunds, W.J., 2008. Social contacts and mixing patterns relevant to the spread of infectious diseases. PLoS Med. https://doi.org/10.1371/journal.pmed.0050074.
Naeem, I., Masood, N., Turan, V., Iqbal, M., 2021. Prospective usage of magnesium potassium phosphate cement combined with Bougainvillea alba derived biochar to reduce Pb bioavailability in soil and its uptake by Spinacia oleracea L. Ecotoxicol. Environ. Saf. https://doi.org/10.1016/j.ecoenv.2020.111723.
Ogen, Y., 2020. Assessing nitrogen dioxide (NO2) levels as a contributing factor to coronavirus (COVID-19) fatality. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138605.
Pakistan Bureau of Statistics, 2017. District Wise Census Results Census.
Perrone, M.G., Gualtieri, M., Consonni, V., Ferrero, L., Sangiorgi, G., Longhin, E., Ballabio, D., Bolzacchini, E., Camatini, M., 2013. Particle size, chemical composition, seasons of the year and urban, rural or remote site origins as determinants of biological effects of particulate matter on pulmonary cells. Environ. Pollut. https://doi.org/10.1016/j.envpol.2013.01.012.
Peters, J.M., Avol, E., Gauderman, W.J., Linn, W.S., Navidi, W., London, S.J., Margolis, H., Rappaport, E., Vora, H., Gong, H., Thomas, D.C., 1999. A study of twelve Southern California communities with differing levels and types of air pollution: II. Effects on pulmonary function. Am. J. Respir. Crit. Care Med. https://doi.org/10.1164/ajrccm.159.3.9804144.
Quality, R.W.A., 2019. World Air Quality Report (Region & City PM2.5 Ranking IQAir Group.
Ramdan, S.H., 2019. Middle East respiratory syndrome Corona virus (MERS-CoV): a review. Germs 1.
Read, J.M., Bridgen, J.R.E., Cummings, D.A.T., Ho, A., Jewell, C.P., 2020. Novel coronavirus 2019-nCoV: early estimation of epidemiological parameters and epidemic predictions. https://doi.org/10.1101/2020.01.23.20018549.
Rocklöv, J., Sjödin, H., Wilder-Smith, A., 2020. COVID-19 outbreak on the Diamond Princess cruise ship: estimating the epidemic potential and effectiveness of public health countermeasures. J. Trav. Med. https://doi.org/10.1093/jtm/taaa030.
Roosa, K., Lee, Y., Luo, R., Kirpich, A., Rothenberg, R., Hyman, J.M., Yan, P., Chowell, G., 2020. Real-time forecasts of the COVID-19 epidemic in China from february 5th to february 24th, 2020. Infect. Dis. Model. https://doi.org/10.1016/j.idm.2020.02.002.
Sánchez-Triana, E., Enriquez, S., Afzal, J., Nakagawa, A., Khan, A.S., 2014. Cleaning Pakistan's Air: Policy Options to Address the Cost of Outdoor Air Pollution, Cleaning Pakistan's Air: Policy Options to Address the Cost of Outdoor Air Pollution. https://doi.org/10.1596/978-1-4648-0235-5.
SanJuan-Reyes, Sindy, , Leobardo Manuel Gómez-Oliván, Islas-Flores, Hariz, 2021. COVID-19 in the environment. Chemosphere 263. https://doi.org/10.1016/j.chemosphere.2020.127973.
Seposo, X., Ueda, K., Sugata, S., Yoshino, A., Takami, A., 2020. Short-term effects of air pollution on daily single- and co-morbidity cardiorespiratory outpatient visits. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138934.
Setti, L., Passarini, F., De Gennaro, G., Barbieri, P., Licen, S., Perrone, M.G., Piazzalunga, A., Borelli, M., Palmisani, J., DI Gilio, A., Rizzo, E., Colao, A., Piscitelli, P., Miani, A., 2020a. Potential role of particulate matter in the spreading of COVID-19 in Northern Italy: first observational study based on initial epidemic diffusion. BMJ Open. https://doi.org/10.1136/bmjopen-2020-039338.
Setti, L., Passarini, F., De Gennaro, G., Barbieri, P., Perrone, M.G., Borelli, M., Palmisani, J., Di Gilio, A., Torboli, V., Fontana, F., Clemente, L., Pallavicini, A., Ruscio, M., Piscitelli, P., Miani, A., 2020b. SARS-Cov-2RNA found on particulate matter of Bergamo in Northern Italy: first evidence. Environ. Res. https://doi.org/10.1016/j.envres.2020.109754.
Shahbaz, A.K., Adnan Ramzani, P.M., Saeed, R., Turan, V., Iqbal, Muhammad, Lewińska, K., Abbas, F., Saqib, M., Tauqeer, H.M., Iqbal, Mutahar, Fatima, M., Rahman, M. ur, 2019. Effects of biochar and zeolite soil amendments with foliar proline spray on nickel immobilization, nutritional quality and nickel concentrations in wheat. Ecotoxicol. Environ. Saf. https://doi.org/10.1016/j.ecoenv.2019.02.025.
Sipra, H., Aslam, F., Syed, J.H., Awan, T.M., 2020. Investigating the implications of COVID-19 on PM2.5 in Pakistan. Aerosol Air Qual. Res. https://doi.org/10.4209/aaqr.2020.07.0459.
Tang, B., Wang, X., Li, Q., Bragazzi, N.L., Tang, S., Xiao, Y., Wu, J., 2020. Estimation of the transmission risk of the 2019-nCoV and its implication for public health interventions. J. Clin. Med. https://doi.org/10.3390/jcm9020462.
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diseases (COVID-19) in China, 2020. Zhonghua Liu Xing Bing Xue Za Zhi. https://doi.org/10.3760/cma.j.issn.0254-6450.2020.02.003.
Turan, V., 2019. Confident performance of chitosan and pistachio shell biochar on reducing Ni bioavailability in soil and plant plus improved the soil enzymatic activities, antioxidant defense system and nutritional quality of lettuce. Ecotoxicol. Environ. Saf. https://doi.org/10.1016/j.ecoenv.2019.109594.
ul, Haq, Z., Tariq, S., Ali, M., Mahmood, K., Batool, S.A., Rana, A.D., 2014. A study of tropospheric NO2 variability over Pakistan using OMI data. Atmos. Pollut. Res. https://doi.org/10.5094/APR.2014.080.
US EPA, 2012. The National Ambient Air Quality Standards for Particle Matter: Revised Air Quality Standards for Particle Pollution and Updates to the Air Quality Index (AQI). Environ. Prot. Agency.
US-EPA, 2012. Revised Air Quality Standards for Particle Pollution and Updates to the Air Quality Index (AQI).
van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E., Munster, V.J., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. N. Engl. J. Med. https://doi.org/10.1056/nejmc2004973.
Wangping, J., Ke, H., Yang, S., Wenzhe, C., Shengshu, W., Shanshan, Y., Jianwei, W., Fuyin, K., Penggang, T., Jing, L., Miao, L., Yao, H., 2020. Extended SIR prediction of the epidemics trend of COVID-19 in Italy and compared with hunan, China. Front. Med. https://doi.org/10.3389/fmed.2020.00169.
Waris, A., Atta, U.K., Ali, M., Asmat, A., Baset, A., 2020. COVID-19 outbreak: current scenario of Pakistan. New Microbes New Infect. https://doi.org/10.1016/j.nmni.2020.100681.
WHO, 2020. WHO Timeline Retrieved from World Health Organization.
World Air Quality Report, 2018. Air Visual . IQ Air AirV Isual. Staad, Switzerland.
World Health Organisation, 2018. WHO global ambient air quality database (update 2018). Ambient Air Qual. Database (Update 2018.
World Health Organization, 2003. Health Aspects of Air Pollution with Particulate Matter , Ozone and Nitrogen Dioxide. Report on a WHO Working Group Bonn.
Wu, Z., McGoogan, J.M., 2020. Characteristics of and important lessons from the coronavirus disease 2019 (COVID-19) outbreak in China. J. Am. Med. Assoc. https://doi.org/10.1001/jama.2020.2648.
Wu, X., Nethery, R., Sabath, B., Braun, D., Dominici, F., 2020a. Exposure to air pollution and COVID-19 mortality in the United States: a nationwide cross-sectional study. Sci. Adv. https://doi.org/10.1101/2020.04.05.20054502.
Wu, X., Nethery, R.C., Sabath, M.B., Braun, D., Dominici, F., 2020b. Exposure to Air Pollution and COVID-19 Mortality in the United States: A Nationwide Cross-Sectional Study. https://doi.org/10.1101/2020.04.05.20054502.
Xie, Z., Li, Y., Lu, R., Li, W., Fan, C., Liu, P., Wang, J., Wang, W., 2018. Characteristics of total airborne microbes at various air quality levels. J. Aerosol Sci. https://doi.org/10.1016/j.jaerosci.2017.11.001.
Xu, Q., Li, X., Wang, S., Wang, C., Huang, F., Gao, Q., Wu, L., Tao, L., Guo, J., Wang, W., Guo, X., 2016. Fine particulate air pollution and hospital emergency room visits for respiratory disease in urban areas in Beijing, China. PLoS One. https://doi.org/10.1371/journal.pone.0153099.
Zeng, J., Huang, J., Pan, L., 2020. How to balance acute myocardial infarction and COVID-19: the protocols from Sichuan Provincial People's Hospital. Intensive Care Med. https://doi.org/10.1007/s00134-020-05993-9.
Zhao, S., Lin, Q., Ran, J., Musa, S.S., Yang, G., Wang, W., Lou, Y., Gao, D., Yang, L., He, D., Wang, M.H., 2020. Preliminary estimation of the basic reproduction number of novel coronavirus (2019-nCoV) in China, from 2019 to 2020: a data-driven analysis in the early phase of the outbreak. Int. J. Infect. Dis. https://doi.org/10.1016/j.ijid.2020.01.050.
Zhong, N.S., Zheng, B.J., Li, Y.M., Poon, L.L.M., Xie, Z.H., Chan, K.H., Li, P.H., Tan, S.Y., Chang, Q., Xie, J.P., Liu, X.Q., Xu, J., Li, D.X., Yuen, K.Y., Peiris, J.S.M., Guan, Y., 2003. Epidemiology and cause of severe acute respiratory syndrome (SARS) in Guangdong, People's Republic of China, in February, 2003. Lancet. https://doi.org/10.1016/S0140-6736(03)14630-2.
Zhong, L., Mu, L., Li, J., Wang, J., Yin, Z., Liu, D., 2020. Early prediction of the 2019 novel coronavirus outbreak in the mainland China based on simple mathematical model. IEEE Access. https://doi.org/10.1109/ACCESS.2020.2979599.
Zhu, Y., Xie, J., Huang, F., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2020.138704.