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Spatiotemporal variability of COVID-19 pandemic in relation to air pollution, climate and socioeconomic factors in Pakistan



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HIGHLIGHTS

- Relationship between air pollution, climate, and socioeconomic factors on COVID-19 cases.
- Modeling of COVID-19 with PM_{2.5}, climatic, socioeconomic factors in provincial cities.
- Vulnerable PM_{2.5} conc. identified for COVID-19 spread in provincial capital (Lahore).
- Relationship of PM_{2.5}, COVID-19 and climatic factors used to predict risky cities in 2021.

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ABSTRACT

Information on the spatiotemporal variability of respirable suspended particulate pollutant matter concentrations, especially of particles having size of 2.5 μm and climate are the important factors in relation to emerging COVID-19 cases around the world. This study aims at examining the association between COVID-19 cases, air pollution, climatic and socioeconomic factors using geospatial techniques in three provincial capital cities and the federal capital city of Pakistan. A series of relevant data was acquired from 3 out of 4 provinces of Pakistan (Punjab, Sindh, Khyber Pakhtunkhwa (KPK) including the daily numbers of COVID-19 cases, PM_{2.5} concentration ($\mu\text{g m}^{-3}$), a climatic factors including temperature ($^{\circ}\text{F}$), wind speed (m/s), humidity (%), dew point (%), and pressure (Hg) from June 1 2020, to July 31 2020. Further, the possible relationships between population density and COVID-19 cases was determined. The generalized linear model (GLM) was employed to quantify the effect of PM_{2.5}, temperature, dew point, humidity, wind speed, and pressure range on the daily COVID-19 cases. The grey relational analysis (GRA)

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GLM model
Correlation
GRA
Geoinformation

was also implemented to examine the changes in COVID-19 cases with PM_{2.5} concentrations for the provincial city Lahore. About 1,92,819 COVID-19 cases were reported in Punjab, Sindh, KPK, and Islamabad during the study period. Results indicated a significant relationship between COVID-19 cases and PM_{2.5} and climatic factors at $p < 0.05$ except for Lahore in case of humidity ($r = 0.175$). However, mixed correlations existed across Lahore, Karachi, Peshawar, and Islamabad. The R^2 value indicates a moderate relationship between COVID-19 and population density. Findings of this study, although are preliminary, offers the first line of evidence for epidemiologists and may assist the local community to expedient for the growth of effective COVID-19 infection and health risk management guidelines. This remains to be seen.

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1. Introduction

Primary cases of pneumonia of unidentified sources were reported in Wuhan, Hubei Province, China late December 2019. Researchers, however, later identified the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) as responsible for this disease in January 2020. The novel coronavirus shows a 70% genomic sequence similarity with SARS-CoV-1 (Briz-Redón and Serrano-Aroca, 2020; Cohen and Normile, 2020). Coronavirus disease, also labeled as COVID-19, is the fifth largest pandemic after the Spanish Flu pandemic, which was started in the year 1918. COVID-19 spread from China to several other countries by human-to-human transmission and mostly affects the respiratory system (Liu et al., 2020; Waris et al., 2020).

Based on the high rate of transmission, COVID-19 was affecting a large population in a short period, and thus World Health Organization (WHO) declared SARS CoV-2 as a Public Health Emergency of International Concern (PHEIC) on 30th January 2020 (Sohrabi et al., 2020; WHO, 2020a). Interestingly, the number of new cases increased 13 times more quickly in other parts of the world as compared to the number of new cases inside China during February 2020. COVID-19 rapid spread has resulted in the pandemic infection of more than 7,15,81,5,32 confirmed cases with 16,18,374 deaths in 208 countries by December 15, 2020 (WHO, 2020b; Zhou et al., 2020). Owing to its rapid spread, WHO on the 11th of March, 2020 declared it as a pandemic (Javed et al., 2020).

The recent spread of COVID-19 infection has caused serious acute respiratory syndrome coronavirus (SARS-CoV) and other severe respiratory illnesses (Huang et al., 2020; Xu et al., 2020). Commonly associated symptoms are fever, cough, fatigue, partial or complete loss of smell and taste, and myalgia at the start of infections (Huang et al., 2020). Evidence suggest that the transmission of COVID-19 from one person to another person is happening through direct contact or droplets (Chan et al., 2020; Lai et al., 2020; Li et al., 2020). For example, a recent study (Wang et al., 2020) reported that person-to-person hospital-associated transmission of COVID-19 was suspected in 41% of patients. According to the WHO officials, there is mounting evidence that the coronavirus can be transmitted by tiny particles suspended in the air. Studies by epidemiologists and scientists have clearly shown that viruses are unconstrained during coughing, talking, and exhalation in microdroplets tiny enough to suspend in the air for some time sufficient to exacerbate the risk of exposure at a distance more than 1–2 m from an infected person (Lindsley et al., 2010; Morawska and Milton, 2020; Yan et al., 2018).

Similar to other parts of the world, Pakistan has been badly hit by this Pandemic and the first case was documented on February 26, 2020, in Pakistan. It is assumed that the rapid increase in the reported COVID-19 cases was due to the mass movement of people to and from two pandemic hit neighboring countries namely Iran and China. Implementation measures (to minimize the spread of

virus transmission) such as wearing the mask, physical distancing, and handwashing, further fueled the number of COVID-19 cases, etc. As of December 15, 2020, there were about 1,98,482 totally confirmed COVID-19 cases in Pakistan with 53,253, 1,28,673, 35,203, 17,796, 7,771/4,799 cases in Sindh, Khyber Pakhtunkhwa (KPK), Punjab, Islamabad, Baluchistan, Azad Jammu and Kashmir (AJK)/Gilgit Baltistan (GB), respectively (MNHS, 2020).

Considering its global threat, the transmission factors of COVID-19 should be made explicit. Based on the studies, it is estimated that the serial interval and incubation period depend on the early epidemics in China (Backer et al., 2020; Li et al., 2020). The sequential interval is the period between the symptom start of the following cases; the incubation duration is the spell from infection to the onset of the symptoms. These are key epidemiological factors that give essential insight to deduce the transmission perspective and estimate the quarantine duration (Nishiura et al., 2020).

Since the onset of this pandemic, intensive efforts are being put forward worldwide to develop a vaccine with limited side effects. The development of a safe and effective vaccine, COVAX (led by WHO, GAVI, and CEPI) will ease the impartial access and distribution of these vaccines to protect people over the world. (WHO, 2020b). Presently, more than 50 COVID-19 vaccine candidates are in trial phases. Recently, Pfizer and BioNTech have found a similar mRNA vaccine against COVID-19 and also reported excellent results on 16 November, with an efficacy of 95% (BBC, 2020). However, the distribution of these vaccines is still a challenge due to its cost, transportation, and storage issues.

Ecological parameters may induce the development of contagious infection outbreaks through altering the host vulnerability and the existence phase of viruses in vitro condition (Zhang et al., 2015). Recent studies suggested that respirable suspended particle pollutants (PM_{2.5}), humidity, temperature, and wind speed were strongly linked with the epidemic of the severe acute respiratory syndrome (SARS) (Mehmood et al., 2020a, 2020b; Shi et al., 2020). The atmospheric factors such as humidity, temperature, or solar irradiation perform inversely to COVID-19 survival. For instance, some recent studies show that COVID-19 transmission is favored by cold and dry weather conditions (Casanova et al., 2010; Ghosh et al., 2020a). Regarding COVID-19 pandemic transmission, Huang et al. (2020) found that the COVID-19 is facilitated in the temperature range from 5 to 15 °C. Another study showed that both temperature and relative humidity factors perform reasonably well for the model prediction of infections and alert in advance to minimize the risk of future COVID-19 pandemic (Huang et al., 2020). However, there is no conclusive evidence of how the climatic factors and air pollution influence COVID-19 transmission. Meanwhile, numerous studies focused on the contribution of climatic factors on COVID-19 transmission over the world with different methods. It can be seen in several studies from China (Shi et al., 2020; Xie and Zhu, 2020) USA (Bashir et al., 2020), Norway, Germany (F. F. Wu et al., 2020a), Brazil, Mexico (Biktasheva, 2020), Turkey and many others around

the world (Ghosh et al., 2020b; Sobral et al., 2020) are not clear on COVID-19 distribution with climatic factors and the WHO emphasized that new findings are urgently required to quantitatively estimate how climatic conditions and respirable particle pollutant (PM_{2.5}) influence the spread of COVID-19.

The ambient particulate matter could play a significant role in the transmission of disease-causing agents. A great deal of literature shows a strong association of fine particles with the incidence of several respiratory health ailments, especially chronic obstructive pulmonary disease (COPD) and asthma (Mehmood et al., 2020a; Gorai et al., 2016). Poor air quality led to an increase in SARS-related deaths as well as a rise in influenza cases in many parts of the world (Landguth et al., 2020). Generally, there are several indicators such as economic, demographic, population, and travel are supposed to be contributing factors to the incidence of developing infectious diseases (Bhadra et al., 2020; Kadi and Khelifaoui, 2020). A massive population with high population density increased population mobility and rapid urbanized well-developed cities are also play a key role in the widespread of epidemic diseases (Buliva et al., 2017). Recently, Raza et al. (2020) found that a relationship between meteorological indicators and the COVID-19 pandemic in Pakistan. However, this study did not take into account the air pollution especially respirable particle pollutant (PM_{2.5}), and socioeconomic factors include population density which has a significant role in the spread of COVID-19. Looking at these factors, the present study was planned to investigate the association among COVID-19, respirable suspended particle pollutant (PM_{2.5}), meteorological, and socioeconomic factors.

The present study aims at investigating how the COVID-19 pandemic distributed in three metropolitans (Karachi, Lahore, and Peshawar) cities representing three provinces Sindh, Punjab, and KPK, respectively. In each provincial city, the climate, air pollution, and socioeconomic are crucial factors, hence, climatic data, particularly temperature (°F), wind speed (m/s), humidity (%), dew point (%), and pressure (Hg) and air pollution include respirable particle pollutant (PM_{2.5}) (µg/m³) and socioeconomic cover population density (per km²) indicators were selected to realize the impact on the transmission of COVID-19 in Pakistan. This work employs a Generalized Linear Model (GLM) using the Poisson log function to explore the relationship among covariate climatic factors, PM_{2.5}, and COVID-19 cases. This study also utilizes the simple linear regression (R²) model to analyze the relationship of population density with COVID-19 distribution at the province level. Furthermore, grey relational analysis (GRA) is implemented for the provincial city Lahore to study the changes in COVID-19 cases concerning PM_{2.5} concentration.

2. Material and methods

2.1. 2.1. Experimental setup

The COVID-19 was declared as a pandemic by WHO and since the reporting of the 1st case in China, it has resulted in severe losses to socio-economic sectors and caused millions of deaths all over the world including Pakistan (WHO, 2020b). The daily confirmed COVID-19 cases in three out of four provinces and Islamabad city of Pakistan from June 1 to July 31, 2020, were selected as the target period. During this pandemic period, the maximum number of COVID-19 cases and deaths were reported in these provinces of Pakistan. The sum of confirmed COVID cases was gathered from data published by the National Health Commission of Pakistan (NIH) ((<http://www.nih.org.pk/Pakistan>). The data on PM_{2.5} (24 h) (µg/m³) having particulate matter < 2.5 µm in aerodynamic diameter were collected from the US consulate offices at Lahore, Karachi, Peshawar, and Islamabad (Fig. 1). The climatic factors

included temperature (°F), wind speed (m/s), humidity (%), dew point (%), and pressure (Hg) were collected from the website (<https://www.wunderground.com/>).

2.2. Datasets & models

This study utilized the GLM, GRG, and Pearson correlation (r) analysis to investigate the complex relationships among PM_{2.5} and climatic conditions because these aspects are still yet to be confirmed due to the emergence of several new COVID-19 strains. The GLM is flexible generalization characteristics with ordinary linear regression, which allows for different variables having error distribution than a normal distribution. This model, equipped with a link function, helps to understand the magnitude of variance for each observation to forecast value. The standard mathematical expression of a GLM is shown in Equations (1) and (2), and link, and the mean function were estimated through Equations (3) and (4).

$$y_i|b \sim \text{Distr}(\mu_i, \frac{\sigma^2}{w_i}) \tag{1}$$

$$g(\mu) = X\beta + Zb + \delta \tag{2}$$

$$X\beta = \ln(\mu) \tag{3}$$

$$\mu = \exp(X\beta) \tag{4}$$

where “y” represents the response vector, and “y_i” indicates *i*th element. The “b” is the random-effects vector. The “Distr” is a definite conditional distribution of y given b. The “μ” shows the conditional mean of y given b, and μ_i is its *i*th element. The “σ²” is the dispersion parameter and “w” is the effective observation weight vector, while the “w_i” is the weight for observation “i”. Herein, COVID-19 cases were selected as dependent variables. Covariate includes PM_{2.5} (µg/m³), temperature (°F), wind speed (m/s), relative humidity (%), dew point (%), and pressure (Hg) and Poisson distribution and link function utilized logarithm function.

This study employed (GRA) to understand the uncertainty problems under the limited information and discrete data particularly for those having disengaged characteristics. It provides a data quantity and quality ranged from black through grey to white. (Liu et al., 2017; Pai et al., 2013). So, uncertainty always occurs due to grade and ranks as one place in the middle, or between the extremes, or in the grey area. Then, the GRA approach gives a clear set of information about system classification. Also, GRA can be employed to establish the relationships between various sequences of information and its coefficients can be applied to estimate the sequence of information which disturbs the system considerably (Javed and Liu, 2018). Equation (5) was used to determine the GRA.

$$\gamma_i^{(j)} = \frac{\Delta x_{\min} + \xi \cdot \Delta x_{\max}}{\Delta i^{(j)} + \xi \cdot \Delta x_{\max}} \tag{5}$$

where “i(j)” is the “j” the value in the “Δi” difference data series. “ξ” is called the distinguishing coefficient (ξ = 0.5).

Pearson’s correlation coefficient (r) was also calculated using Equation (6):

$$r_{xy} = \frac{\text{cov}(x, y)}{\sqrt{\text{var}(x)} \cdot \sqrt{\text{var}(y)}} \tag{6}$$

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.

Also, this study aims to analyze the population density to

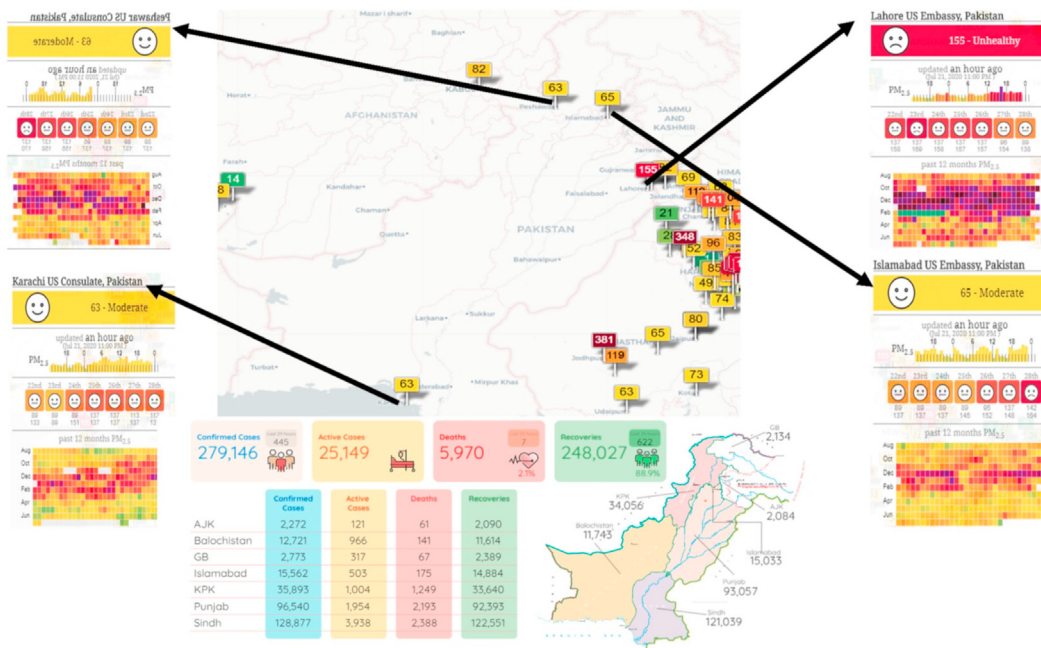


Fig. 1. Locations of PM_{2.5} concentrations data sites at Lahore, Karachi, Peshawar and Islamabad US consulates offices and COVID-19 cases distributions in Pakistan February 26 to June 30, 2020 (Sources: <http://covid.gov.pk/stats/pakistan>; Pakistan air quality monitoring US-EPA <https://aqicn.org/>).

Table 1 Descriptive analysis for daily COVID-19 cases, PM_{2.5} concentrations, and climatic factors in Punjab (Lahore), Sindh (Karachi) Khyber Pakhtunkhwa (KPK) (Peshawar) and Islamabad from June 1 to July 31, 2020.

	PM _{2.5} conc. (µgm ⁻³)	Temperature (°F)	Dew point (%)	Humidity (%)	Wind speed (m/s)	Pressure (Hg)	COVID-19 Cases
Lahore							
Mean	124.7	88.8	72.7	61.0	9.2	28.8	1070.9
Std. Deviation	29.9	4.9	4.1	11.1	2.7	0.2	747.1
Range	123.0	20.8	15.7	45.0	12.5	1.2	2589.0
Minimum	49.0	78.2	63.4	36.7	4.5	27.8	116.0
Maximum	172.0	99.0	79.1	81.7	17.0	29.0	2705.0
Percentiles							
25	103.5	84.9	70.9	53.9	6.9	28.7	420.0
50	129.5	88.7	74.0	61.4	8.8	28.8	893.0
75	148.0	92.3	75.7	70.2	10.8	28.8	1647.0
Karachi							
Mean	70.6	90.4	75.6	63.1	11.3	29.3	1502.7
Std. Deviation	12.6	1.4	1.5	5.0	3.0	0.7	666.8
Range	49.0	8.1	7.8	26.7	12.9	4.8	2768.0
Minimum	49.0	85.3	71.9	53.2	6.0	24.8	270.0
Maximum	98.0	93.4	79.7	79.9	18.9	29.6	3038.0
Percentiles							
25	60.8	89.6	74.8	59.9	9.2	29.4	1003.0
50	70.0	90.5	75.4	62.1	11.0	29.4	1468.0
75	82.3	91.3	76.7	65.8	12.9	29.5	2135.0
Peshawar							
Mean	118.0	89.8	67.2	48.8	9.6	19.2	388.1
Std. Deviation	21.9	3.9	5.1	8.3	2.2	9.6	197.0
Range	106.0	19.4	21.6	36.3	8.2	28.6	937.0
Minimum	62.0	79.2	56.3	30.6	5.9	0.0	98.0
Maximum	168.0	98.6	77.9	66.9	14.1	28.6	1035.0
Percentiles							
25	106.0	87.7	63.0	42.5	7.9	15.9	218.5
50	118.0	89.7	67.4	48.5	9.9	22.1	371.0
75	134.0	92.5	71.2	55.9	11.2	27.9	531.5
Islamabad							
	PM _{2.5} conc.(µgm ⁻³)	Temperature (°F)	Humidity (%)	Wind speed (m/s)	Pressure (Hg)	COVID-19 Cases	
Mean	94.2	67.5	64.3	4.4	1015.4	199.3	
Std. Deviation	16.4	5.5	8.3	1.8	4.9	175.6	
Range	95.0	24.8	33.4	9.4	24.9	752.0	
Minimum	51.0	56.5	52.5	1.6	998.6	19.0	
Maximum	146.0	81.4	85.8	11.0	1023.5	771.0	
Percentiles							
25	83.0	63.7	58.2	3.0	1013.5	59.0	
50	94.0	67.4	62.7	4.0	1015.9	117.0	
75	104.5	71.7	68.9	5.2	1018.6	305.5	

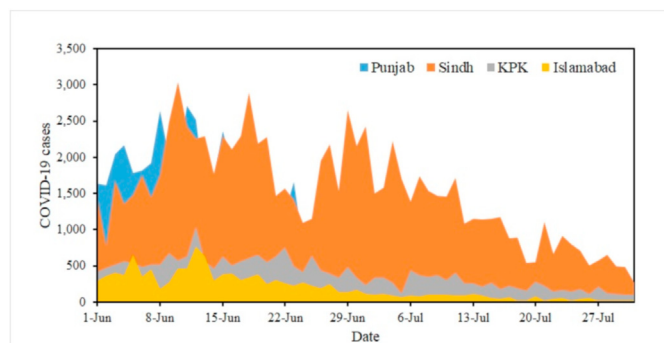


Fig. 2. COVID-19 cases in Punjab, Sindh, KPK and Islamabad during June1 to July 31,2020.

explore whether any correlation between COVID-19 cases in Pakistan with population density exists or not and if yes, we will consider modeling between the COVID-19 cases in Pakistan (dependent variables) with population density (independent variable). For this, we adopted the population density for Punjab, Sindh, KPK and Islamabad are 445.01 km², 392.05 km², 360.93 km², 906 km² respectively. This study also utilized a simple linear regression model (Schneider et al., 2010) to demonstrate the impact of population density (per sq km) on the number of cases of COVID-19 cases as shown in Equation (7):

$$Y = B + aX \tag{7}$$

where “Y” is the dependent variable that denotes the number of cases of COVID-19, and X is the independent variable that represents population density “B” is the constant.

3. Results and discussion

3.1. Temporal distribution of daily COVID-19 cases, PM_{2.5} concentrations, and climatic factors across major cities/provincials

Table 1 summarizes the descriptive analysis of daily COVID-19 confirmed cases, PM_{2.5}, and climatic factors. This study investigated 1,92,819 COVID-19 confirmed cases (around 3,160 cases each day) in three Pakistani provincial cities from June 01 to July 30, 2020. Fig. 2 shows the trend of total COVID-19 cases in Punjab, Sindh, KPK, and Islamabad. It indicated a rapid increase in the total COVID-19 cases from June 1, 2020, to July 30, 2020, in Punjab, KPK, and Islamabad except for June 21 to June 25 in Sindh. As can be observed COVID-19 cases decrease due to the implementation of certain community measures. Afterward, COVID-19 cases were increased at a decreasing rate. It is evident that the total COVID-19 cases were higher in Sindh followed by Punjab, KPK, and Islamabad. Overall, the average COVID-19 cases per day in Punjab, Sindh, KPK, and Islamabad were 1,071, 1,503, and 199, respectively. However, it can be seen that the Punjab and Sindh provinces were mostly affected by the COVID-19.

The PM_{2.5} concentration changed significantly during the selected period with (IQR) of 60.75 μg/m³ (25 percentile), 70 μg/m³ (50 percentile), 82.25 μg/m³ (75 percentile) for the three provincial cities of Pakistan. The mean minimum PM_{2.5} concentrations were recorded more for Karachi (70.6 μg/m³) followed by Islamabad (94.2 μg/m³), Peshawar (118.0 μg/m³) and Lahore (124.7 μg/m³). Climatic factors i.e., temperature, humidity, wind speed, dew point and pressure ranged from 56 °F to 99 °F, 30%–85%, 1.5 m/s to 18.9 m/s, 56.3% to 79.7%, and 7.1 to 40.29 Hg, respectively.

Average temperature was higher in Karachi (90.4 °F) followed by Peshawar (89.8 °F), Lahore (88.8 °F), and Islamabad (67.5 °F).

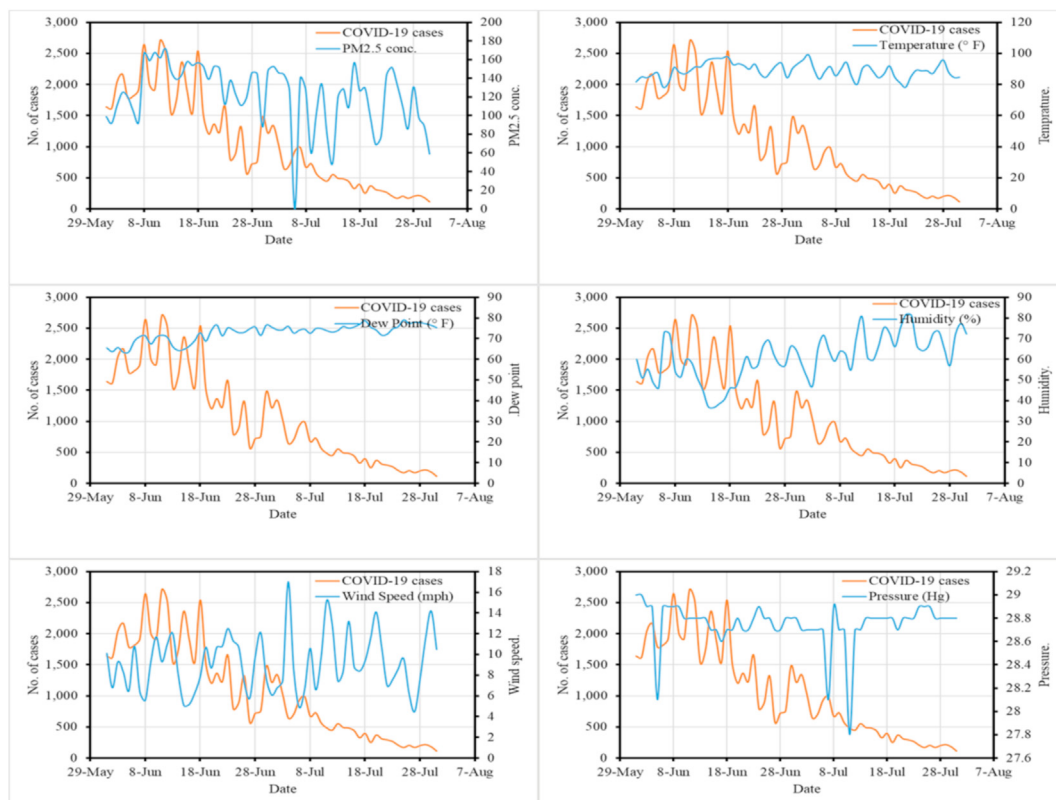


Fig. 3. The time series distribution of daily COVID-19 confirmed cases, PM_{2.5} concentrations, and climate factors in 4 cities of 3 of provinces from June 1 to July 31, 2020.

Average dew point for Karachi, Lahore, and Peshawar was found 72.7%,75.6%, and 67.2% respectively. The dew point data for Islamabad were unavailable. Average higher humidity was noted for Islamabad (64.3%), Karachi (63.1%), Lahore (61.0%), and Peshawar (48.8%). Wind speed obtained (11.3 m/s), (9.6 m/s), (9.2 m/s), and (4.4 m/s) for Karachi, Peshawar, Lahore, and Islamabad, respectively. Finally, the average maximum pressure was seen (1015.4 Hg) for Islamabad, (29.3 Hg) for Karachi (28.8 Hg) for Lahore, and (19.2 Hg) for Peshawar.

Fig. 3 illustrated the time series distribution of daily COVID-19 cases, PM_{2.5}, and climatic factors in Lahore (Punjab). The epidemic curve of COVID-19 daily new cases reached a peak (June 11) during the target study period, with 2705 active cases. The COVID-19 cases with PM_{2.5} and wind speed show a good trend from June 1 to June 19, and June 1 to June 28, respectively, and the same trend was recorded for humidity, especially from June 1 to June 13. However, temperature, pressure, and showed an inverse trend with COVID-19 daily cases.

The GLM offers the dependent variable having non-normal distribution. The GLM results suggested that COVID-19 cases have a significant relationship with PM_{2.5} and climatic factors at $p < 0.05$ against this hypothesis except for Lahore in the case of humidity ($p = 0.175$) (Table 2). The Std error values ranged from 0.00 to 0.035 for Lahore, while for Karachi these varied from 0.002 to 0.319. This model provides useful information to understand the complex relationship among different covariates and it is expected to solve

Table 2
Generalized Linear Model (GLM) parameters estimates for Lahore Karachi, Peshawar and Islamabad.

Parameter	B	Std. Error	95% Wald Confidence Interval		df	Sig.
			Lower	Upper		
Lahore						
(Intercept)	22.628	1.492	19.703	25.553	1.000	0.000
PM _{2.5} conc. (µgm ⁻³)	0.004	0.000	0.003	0.005	1.000	0.000
Temperature (°F)	0.095	0.019	0.058	0.132	1.000	0.000
Dew point (%)	-0.258	0.021	-0.299	-0.218	1.000	0.000
Humidity (%)	0.013	0.009	-0.006	0.031	1.000	0.175
Wind speed (m/s)	0.017	0.004	0.011	0.024	1.000	0.000
Pressure (Hg)	-0.241	0.035	-0.310	-0.172	1.000	0.000
Karachi						
(Intercept)	-573.10	10.736	-594.149	-552.0	1.000	0.000
PM _{2.5} conc.	-0.013	0.002	-0.016	-0.010	1.000	0.000
Temperature	-0.611	0.067	-0.743	-0.479	1.000	0.000
Dew point	0.949	0.066	0.819	1.078	1.000	0.000
Humidity	-0.265	0.031	-0.326	-0.205	1.000	0.000
Wind speed	0.311	0.006	0.299	0.323	1.000	0.000
Pressure	19.504	0.319	18.880	20.129	1.000	0.000
Peshawar						
(Intercept)	10.441	0.021	10.400	10.483	1.000	0.000
PM _{2.5} conc.	0.002	0.000	0.002	0.002	1.000	0.000
Temperature	-0.025	0.000	-0.026	-0.024	1.000	0.000
Dew point	-0.035	0.000	-0.035	-0.034	1.000	0.000
Humidity	-0.008	0.000	-0.009	-0.008	1.000	0.000
Wind speed	0.016	0.000	0.015	0.016	1.000	0.000
Pressure	0.003	0.000	0.003	0.003	1.000	0.000
Islamabad						
(Intercept)	10.441	0.021	10.400	10.483	1.000	0.000
PM _{2.5} conc.	0.002	0.000	0.002	0.002	1.000	0.000
Temperature	-0.025	0.000	-0.026	-0.024	1.000	0.000
Dew point	-0.035	0.000	-0.035	-0.034	1.000	0.000
Humidity	-0.008	0.000	-0.009	-0.008	1.000	0.000
Wind speed	0.016	0.000	0.015	0.016	1.000	0.000
Pressure	0.003	0.000	0.003	0.003	1.000	0.000

Dependent Variable: COVID-19 Cases; Model: (Intercept); Covariates: PM_{2.5} conc. Temperature, Dew point, Humidity, Wind speed, Pressure a. Fixed at the displayed value $p < 0.05$.

the complex relationship for future studies.

The experimental data have been normalized for both PM_{2.5} and COVID-19 cases for Lahore using grey relational generations. Lahore city is selected because it has badly affected during the study period. Table 3 shows that the result being utilized for optimizing the multi-responses and it is transformed into a single grade. This analysis indicates the complex relationship between COVID-19 and PM_{2.5} at different time intervals and how the COVID-19 cases were changed with PM_{2.5} concentration during the target period. The normalized data set have been used further to calculate grey relational coefficients. Next, GRG has been determined from the results of grey relational coefficients.

3.2. Associations of PM_{2.5} (µg/m³) concentrations and climatic factors with COVID-19

The Pearson correlation coefficient (r) for COVID-19 cases, PM_{2.5}, and climatic factors are shown in Table 3. As can be observed COVID-19 cases were negatively correlated with dew point ($r = -0.513$), humidity ($r = -0.401$), wind speed ($r = -0.036$), pressure ($r = -0.325$) and were positively correlated with PM_{2.5} ($r = 0.244$) and temperature ($r = 0.103$) for Lahore. Contrary to Lahore, PM_{2.5} ($r = -0.237$) and temperature ($r = -0.343$) were negatively correlated with COVID-19 cases in Karachi. In the case of Peshawar, all parameters were negatively correlated with COVID-19 cases except for PM_{2.5} ($r = 0.08$) and pressure ($r = 0.07$), while in capital city Islamabad surrounded by mountains, humidity ($r = 0.386$) and wind speed ($r = 0.381$) were correlated positively with a number of COVID-19 cases (Fig. 4). In a similar study, Tosepu et al. (2020) applied climate-related factors in the case of Jakarta. However, this study focused on COVID-19 cases with these factors for the provincial level (Punjab, Sindh, KPK, Islamabad Capital Territory). Temperature is a crucial climatic factor influencing COVID-19 spread (Shi et al., 2020). The results showed that PM_{2.5} concentration and temperature have moderate to weak correlations for Lahore (Punjab). The relationship between temperature and COVID-19 cases offers valuable information in terms of its prevalence over different cities of Pakistan. In Lahore, the temperature was observed positively correlated ($r = 0.103$) with COVID-19 cases, and Lahore representing >35.51% of the total COVID-19 cases in Pakistan. Kim et al. (2016) previously demonstrated that the increase in temperature was connected with an increased risk of mortality which is associated with cardiovascular and respiratory diseases over thirty East Asian countries.

Contrary to this study, a positive correlation was found between total cases and temperature in New York, USA, which was badly affected by COVID-19 (Bashir et al., 2020). Meanwhile, PM_{2.5} concentrations are closely linked with COVID-19 cases in Lahore (Punjab) and the temperature has less influence on COVID-19 spread. It implies that the COVID-19 cases increased in Punjab due to a rise in PM_{2.5} concentrations, which was in line with Laxmipriya and Narayanan (2020), and Zoran et al. (2020) studies in the case of Lahore, Karachi, and Peshawar, Islamabad, Chennai, Milan in Pakistan and India, Italy respectively. The other provincial cities have no correlation existed between COVID-19 cases and PM_{2.5} concentrations. However, the current study selected only (PM_{2.5}), although multipollutant analyses are certainly warranted. It has also been observed that the health risk would be greater for those particles with particle sizes of 2.5 µm or less, which are generally stated as PM_{2.5}.

In the case of Islamabad, a moderate correlation existed for wind speed and humidity suggested that there is a certain impact on COVID-19 transmission. Raza et al. (2020) found that there is no correlation exists between humidity and COVID-19 cases in Pakistan. Contrary to this, results obtained in the present study

Table 3
Pearson Correlation analysis (r) of COVID-19 cases with PM_{2.5} concentration and climatic factors.

	PM _{2.5} conc. (µgm ⁻³)	Temperature (°F)	Dew point (%)	Humidity (%)	Wind speed (m/s)	Pressure (Hg)	COVID-19 cases
Lahore							
PM _{2.5} conc.	1.00						
Temperature	.480**	1.00					
Dew point	-0.14	0.09	1.00				
Humidity	-.488**	-.743**	.591**	1.00			
Wind speed	0.00	-.387**	0.15	.422**	1.00		
Pressure	-0.09	-0.15	-0.01	0.09	-0.07	1.00	
COVID-19 Cases	0.24	0.10	-.513**	-.401*	-0.04	-0.33	1.00
Peshawar							
PM _{2.5} conc.	1.00						
Temperature	0.14	1.00					
Dew point	0.10	0.28	1.00				
Humidity	-0.03	-0.38	0.77	1.00			
Wind speed	0.26	-0.38	0.25	0.46	1.00		
Pressure	-0.09	-0.55	0.02	0.37	0.21	1.00	
COVID-19 Cases	0.08	-0.26	-0.57	-0.37	-0.04	0.07	1.00
Karachi							
PM _{2.5} conc.	1.00						
Temperature	0.23	1.00					
Dew point	-0.44	-0.43	1.00				
Humidity	-0.37	-0.84	0.83	1.00			
Wind speed	-0.13	0.05	0.04	-0.05	1.00		
Pressure	0.06	-0.05	-0.07	-0.01	0.10	1.00	
COVID-19 Cases	-0.27	-0.34	0.12	0.30	0.09	0.02	1.00
Islamabad							
	PM _{2.5} (µgm ⁻³)	Temperature (°F)	Humidity (%)	Wind speed (m/s)	Pressure (Hg)	COVID-cases	
PM _{2.5} conc.	1						
Temperature	0.1704	1					
Humidity	-0.114	-0.7	1				
Wind speed	0.0844	-0.43	0.46	1			
Pressure	0.1666	0.26	-0.3	-0.442	1		
COVID-19 Cases	-0.162	-0.56	0.39	0.3815	-0.53	1	

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

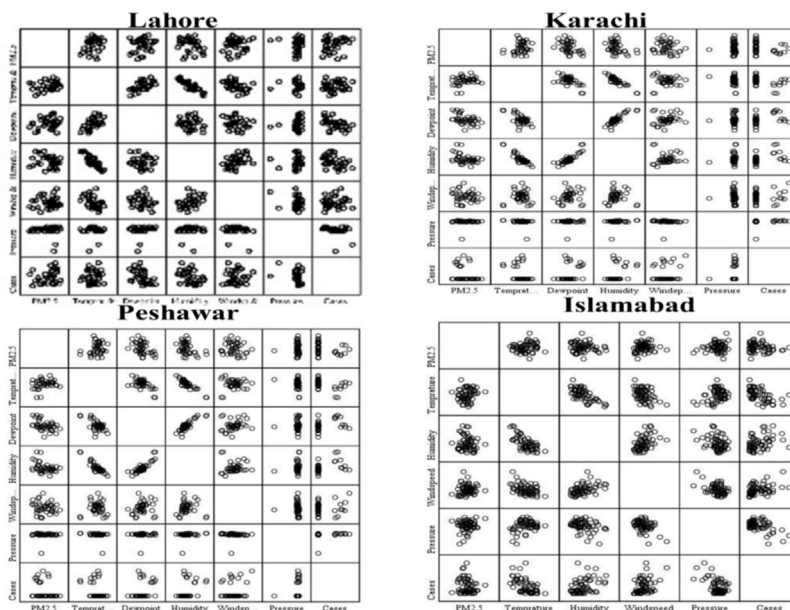


Fig. 4. Correlation analysis (r) analysis daily COVID-19 confirmed cases, PM_{2.5} concentrations, and climatic factors in Lahore, Karachi, Peshawar and Islamabad.

imply that humidity has played an important role in the transmission of COVID-19 in Islamabad. The humidity showed a significant impact on COVID-19 spread (Chen et al., 2020). In China, humidity significantly influenced the diffusion of COVID-19 (Wang et al., 2020). Sajadi et al., 2020) also mentioned the nexus between

humidity and respiratory viruses. Likewise, humidity, there is some correlation that existed between COVID-19 cases and wind. The present study results suggest that wind speed provides a favorable environment for COVID-19 spread in Islamabad and these results show good agreement with the findings of Rendana (2020).

Table 4
Grey relational analysis (GRG) for PM_{2.5} concentration and COVID-19 in Lahore.

Sr. No.	Evaluation of Δ0i (PM _{2.5} conc.)	Evaluation of Δ0i (Cases)	Grey relational coefficient (PM _{2.5} conc.)	Grey relational coefficient (Cases)	Grey relational grade	rank
1	0.551	0.001	0.338	0.998	0.668	53
2	0.555	0	0.337	0.998	0.668	58
3	0.557	0	0.336	0.999	0.667	59
4	0.554	0	0.337	0.998	0.668	57
5	0.545	0.001	0.341	0.996	0.669	49
6	0.554	0	0.337	0.998	0.668	56
7	0.563	0	0.333	1	0.667	60
8	0.549	0.001	0.339	0.997	0.668	50
9	0.533	0.002	0.346	0.993	0.669	44
10	0.524	0.003	0.349	0.991	0.67	36
11	0.552	0.001	0.338	0.998	0.668	54
12	0.543	0.001	0.341	0.996	0.669	46
13	0.516	0.003	0.353	0.988	0.671	32
14	0.532	0.002	0.346	0.993	0.67	43
15	0.551	0.001	0.338	0.998	0.668	52
16	0.529	0.002	0.347	0.992	0.67	38
17	0.512	0.004	0.355	0.987	0.671	31
18	0.55	0.001	0.339	0.997	0.668	51
19	0.512	0.004	0.355	0.987	0.671	30
20	0.497	0.005	0.362	0.981	0.671	24
21	0.5	0.005	0.36	0.982	0.671	27
22	0.49	0.006	0.365	0.978	0.672	21
23	0.544	0.001	0.341	0.996	0.669	47
24	0.441	0.014	0.39	0.954	0.672	14
25	0.475	0.008	0.372	0.972	0.672	16
26	0.528	0.002	0.348	0.992	0.67	37
27	0.409	0.02	0.408	0.935	0.671	25
28	0.414	0.019	0.405	0.938	0.671	23
29	0.425	0.016	0.399	0.945	0.672	20
30	0.552	0.001	0.338	0.998	0.668	55
31	0.491	0.006	0.365	0.979	0.672	22
32	0.498	0.005	0.361	0.982	0.671	26
33	0.47	0.009	0.375	0.969	0.672	12
34	0.394	0.023	0.417	0.925	0.671	29
35	0.435	0.015	0.393	0.951	0.672	17
36	0.469	0.009	0.375	0.969	0.672	11
37	0.471	0.009	0.374	0.97	0.672	13
38	0.425	0.016	0.398	0.945	0.672	19
39	0.53	0.002	0.347	0.992	0.67	40
40	0.432	0.015	0.394	0.949	0.672	18
41	0.346	0.035	0.448	0.89	0.669	45
42	0.441	0.014	0.39	0.954	0.672	15
43	0.523	0.003	0.35	0.99	0.67	35
44	0.376	0.027	0.428	0.912	0.67	33
45	0.354	0.033	0.443	0.896	0.67	42
46	0.372	0.028	0.431	0.91	0.67	34
47	0.18	0.097	0.61	0.744	0.677	9
48	0.308	0.046	0.478	0.859	0.669	48
49	0.155	0.109	0.645	0.72	0.683	5
50	0.355	0.032	0.443	0.897	0.67	41
51	0.396	0.022	0.415	0.927	0.671	28
52	0.355	0.032	0.442	0.897	0.67	39
53	0.141	0.117	0.666	0.707	0.687	4
54	0.025	0.189	0.917	0.599	0.758	1
55	0	0.208	1	0.575	0.788	0
56	0.141	0.117	0.667	0.707	0.687	3
57	0.167	0.103	0.628	0.732	0.68	7
58	0.069	0.159	0.802	0.64	0.721	2
59	0.202	0.087	0.583	0.765	0.674	10
60	0.176	0.099	0.615	0.741	0.678	8
61	0.158	0.107	0.64	0.724	0.682	6

Table 4 shows the degree of correlation between COVID-19 cases and PM_{2.5} concerning grey relational grade (GRD) and ranks. The mean GRD was 0.675 during the study period which indicates that there is a good correlation exist between COVID-19 cases and PM_{2.5}. The grade helps to categorize the changes in between COVID-19 cases and PM_{2.5} (Table 4).

The COVID-19 pandemic has produced an enormous health and economic burden over the world. In this retrospective study, the relationship between COVID-19 cases and PM_{2.5} and climatic

factors were investigated. These findings suggested a significantly varied effect of PM_{2.5} and climatic factors over confirmed COVID-19 cases in different cities of Pakistan. The GLM model results and time-series distribution emphasized that the impact of PM_{2.5} and climatic factors should be considered when estimating the infection by COVID-19.

The results are consistent with the other studies (Frontera et al., 2020; Zhu et al., 2020), which showed a significant association between PM_{2.5} and COVID-19 infection across 120 cities in China.

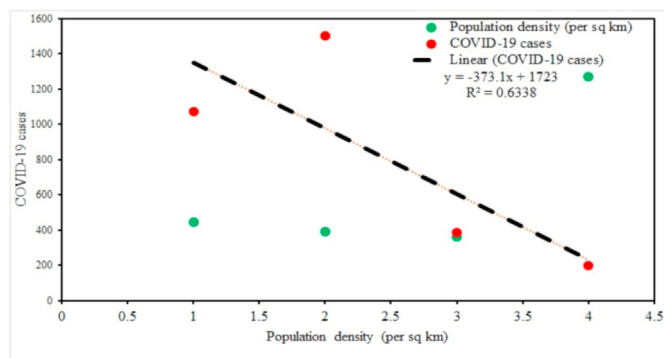


Fig. 5. The relationship (R^2) between COVID-19 cases and population density during June 1 to July 31, 2020.

Moreover, these study results are also in line with the hypothesis put forward by Frontera et al. (2020), who stated that a pollutant-rich atmosphere may promote indirect viral diffusion, besides, to direct (individual to individual) and may be conducive for the risk of infection spread. It was noted that a $10 \mu\text{g m}^{-3}$ increase in pollution concentration led to a statistically significant increase in daily counts of the confirmed symptomatic Corona-positive cases. Similarly, (Wu et al. (2020) found an increase of $1 \mu\text{g m}^{-3}$ of $\text{PM}_{2.5}$ corresponding to a 15% increase in COVID-19 deaths. Several recent studies indicated that COVID-19 cases increased with increasing levels of $\text{PM}_{2.5}$ (Conticini et al., 2020; Zhu et al., 2020). Overall, mixed correlations are existing across Lahore, Karachi, Peshawar, and Islamabad that could be attributed to varied climatic conditions, and COVID-19 data were gathered at the province level.

The R^2 value indicates that the relationship between COVID-19 and population density was moderate (Fig. 5) which suggests that COVID-19 cases are higher in those cities where population density is more. From the current study analysis, it could be deduced that the COVID-19 cases are not only affected by climatic and air pollution factors but also influenced by geographical landscapes, economic conditions, demographic disease variations, genetic factors, health care system, number of testing and age differences, etc. However, there is no fundamental direct and explicit method of catching different possible dependent factors. More investigation on these characteristics is obligatory to address the stated issues.

However, numerous limitations should not be overlooked. Firstly, there are few imperative factors that may affect the distribution of the COVID-19 cases including community interventions, health care system, etc. So, these should be observed in future studies. Secondly, the retrospective time-series design was employed in current study, which might have ecological fallacy up to some extent. Thirdly, besides, it is challenging to gather $\text{PM}_{2.5}$ and climate factors data at a discrete level. The current study depicted that $\text{PM}_{2.5}$ might affect the COVID-19 cases across major cities of Pakistan and other cities with similar climatic conditions in the region, warranting further detailed studies over a large area.

4. Concluding remarks

To the best of our knowledge, this is the first study that examined the complex relationship of $\text{PM}_{2.5}$ and climate factors on the COVID-19 cases in major cities/provinces of Pakistan. The results indicate that the daily COVID-19 is positively associated with $\text{PM}_{2.5}$ and some climatic factors which imply that climate is an important factor in determining the incidence rate of COVID-19 in Pakistan. Overall, there are mixed correlations found in Lahore, Karachi, Peshawar, and Islamabad. In summary, our findings suggest the

$\text{PM}_{2.5}$ concentrations may be one of the important factors affecting the COVID-19 cases across cities/provinces of Pakistan. The findings reported herein motivate the implementation of additional studies to explore why in some cities/provinces of Pakistan, and more widely in the world, the virus spread is different. This approach that excerpts information from the residuals can assist to quantitatively institute if the changes in climate and air pollution factors contributing to weakening the virus spread in different cities/provincial areas safe by the virus. Those results can endorse further studies in other regions of the world also testing other air pollution-related factors especially sulfuric dioxide, nitrogen dioxide, and tropospheric ozone, etc. It is also imperative to emphasized that both the climate and air-pollution parameters are additional key factors affecting the COVID-19 pandemic transmission. However, their effect is still marginal, so all the epidemiological research direction should not be ignored and have the major role. The methodological framework adopted here can be a good paradigm to explore other unidentified factors. Further, this study will help both epidemiologists, environmentalists, meteorologists, and medical doctors to understand the changing pattern of new different COVID-19 strains under different climatic conditions.

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Availability of data and materials

The datasets generated ($\text{PM}_{2.5}$ concentrations and COVID-19 cases data) during 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/>).

Ethical approval

The COVID-19 positive case 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.

CRedit authorship contribution statement

Khalid Mehmood: Conceptualization, Methodology, Investigation, Writing - original draft, Data curation, Visualization, Writing - review & editing. **Yansong Bao:** Supervision, Conceptualization, Validation, Writing - review & editing, Project administration, Methodology, Resources. **Muhammad Mohsin Abrar:** Investigation, Software, Writing - review & editing. **George P. Petropoulos:** Investigation, Writing - review & editing. **Saifullah:** Investigation, Software, Writing - review & editing. **Ahmad Soban:** Investigation, Software, Writing - review & editing. **Shah Saud:** Investigation, Software, Writing - review & editing. **Zalan Alam Khan:** Investigation, Software, Writing - review & editing. **Shah Masud Khan:** Investigation, Software, Writing - review & editing. **Shah Fahad:** Conceptualization, Methodology, Validation, Writing - review & editing.

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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