Geographic information system-based analysis of COVID-19 cases in India during pre-lockdown, lockdown, and unlock phases

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A B S T R A C T

Objective: The World Health Organization formally announced the global COVID-19 pandemic on March 11, 2020 due to widespread infections. In this study, COVID-19 cases in India were critically analyzed during the pre-lockdown (PLD), lockdown (LD), and unlock (UL) phases.
Method: Analyses were conducted using geospatial technology at district, state, and country levels, and comparisons were also made with other countries throughout the world that had the highest infection rates. India had the third highest infection rate in the world after the USA and Brazil during UL2.0–UL3.0 phases, the second highest after the USA during UL4.0–UL5.0 phases, and the highest among South Asian Association for Regional Cooperation (SAARC) countries in PLD–UL5.0 period.
Results: The trend in the number of COVID-19 cases was associated with the population density where higher numbers tended to be record in the eastern, southern, and west–central parts of India. The death rate in India throughout the pandemic period under study was lower than the global average. Kerala reported the maximum number of infections during PLD whereas Maharashtra had the highest numbers during all LD and UL phases. Eighty percent of the cases in India were concentrated mainly in highly populous districts.
Conclusion: The top 25 districts accounted for 70.99%, 69.38%, 54.87%, 44.23%, 40.48%, and 38.96% of the infections from the start of UL1.0 until the end of UL phases, respectively, and the top 26–50 districts accounted for 6.38%, 6.76%, 11.23%, 12.98%, 13.40%, and 13.61% of cases in these phase, thereby indicating that COVID-19 cases spread during the UL period. By October 31, 2020, Delhi had the highest number of infections, followed by Bengaluru Urban, Pune, Mumbai, Thane, and Chennai. No decline in the infection rate occurred, even in UL5.0, thereby indicating a highly alarming situation in India.

Introduction

World Health Organization (WHO) declaration

On February 11, 2020, the WHO officially referred to the disease caused by novel coronavirus 2019 as COVID-19 and the Coronavirus Study Group of the International Committee advised the name of the virus as SARS-CoV-2 (Di Ferrante et al., 1975). The WHO formally announced the global COVID-19 pandemic on March 11, 2020.

Coronaviruses have a single-stranded RNA structure and they can infect humans as well as a huge range of animals (Kooraki et al., 2020). Four diverse genera of coronaviruses have been identified comprising *Alphacoronavirus*, *Betacoronavirus*, *Gammacoronavirus*, and *Deltacoronavirus*. The first two genera may have originated from mammals, particularly bats, whereas the latter two could have come from pigs and birds (Harapan et al., 2020). Betacoronaviruses as well as other virus subtypes can cause severe disease and fatalities. SARS-CoV-2 is a member of the *Betacoronavirus* genus.

Millions of people were infected within a few months of the start of the COVID-19 pandemic, where hundreds of thousands died and millions lost their jobs due to various restrictions imposed across the world (Harapan et al., 2020). COVID-19 is one of the most infectious diseases and it severely affects certain demographics such as senior citizens, infants, and people with serious health conditions. The only means of relieving the COVID-19 pandemic is developing an effective vaccine and distributing it equitably across the world, which demands urgent commitment and investment from countries and international organizations such as the WHO. Globally, the WHO has been

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tracking more than 170 candidate vaccines and more than 36 were in various phases of human clinical trials by October 31, 2020. Pharmaceutical firms in several countries have accelerated their processes to develop candidate vaccines for SARS-CoV-2.

India's response

There have been many global hotspots for COVID-19 cases but India reported its first positive case on January 27, 2020. India is the largest democracy and the second most populous country throughout the world, and thus it highly vulnerable to outbreaks of infectious diseases. During the early stage comprising the pre-lockdown (PLD) period in India, COVID-19 cases were mainly reported from people with a recent history of international travel. COVID-19 screening for passengers was initiated at airports and symptomatic cases were isolated whereas asymptomatic travelers were advised to undergo home quarantine. Within a very short time, some government authorized laboratories started limited real-time polymerase chain reaction (RT-PCR) testing in India. The required reagents for laboratory diagnostics were rapidly purchased, distributed, and deployed across the country through centralized planning by the Government of India (GoI).

At the epidemic stage, the GoI and research community prepared to implement control and prevention measures for COVID-19 infections in India. On March 22, 2020, a countrywide voluntary public curfew was requested by the prime minister of India to make the whole population aware of COVID-19. On March 25, 2020, the GoI initiated a synchronized countrywide lockdown (LD) phase 1.0 (LD1.0) for 21 days to limit the movement of the entire population as a preventive measure (Rai et al., 2020; Chinazzi et al., 2020) and all services were suspended except essential services. Other preventive measures were also implemented across the country, such as wearing masks and hand gloves, using hand sanitizer, maintaining social distancing, and controlling mass gatherings, and the number of infections slowed significantly during LD1.0. On April 15, 2020, the GoI extended the LD period to LD2.0 for a further period of 19 days on the recommendation of state governments and other advisory committees of the GoI.

LD2.0 was imposed under the Disaster Management Act, 2005 (DM Act) to fight the COVID-19 pandemic. The DM Act allowed the GoI to take necessary measures to effectively manage the disaster situation in the country by coordinating with national/state agencies and international organizations. LD3.0 was further extended for a period of two weeks from May 4, 2020, and all 727 districts across the country were divided into three zones (green, orange, and red) depending on the infection rate. On May 18, 2020, LD4.0 was imposed for a further period of two weeks by the GoI. During the LD1.0–LD4.0 phases, the entire land transport system was stopped, industries were closed, air flights were cancelled, and public gatherings were completely suspended.

On June 1, 2020, due to the economic requirements of the country, the GoI announced some relaxations in the green and orange zones with the conditional resumption of limited services, and this resumption phase was referred to as unlock (UL) phase 1.0 (UL1.0). The second phase of UL i.e. UL2.0, was declared for July 1–31, 2020, with the further easing of restrictions. Limited international travel was also permitted in UL2.0 as part of the Vande Bharat Mission. UL3.0 was announced for the month of August 2020, and permission was given for the reopening of gymnasiums, yoga centers, and all inter-and intra-state travel. On August 29, 2020, the GoI issued guidelines for activities permitted in UL4.0 (September, 2020), where LD measures were continued in containment zones. Regular hand washing and other precautionary measures were made compulsory in public places, workplaces, and public transport. UL5.0 was announced for the month of

October 2020 with further relaxation of movements and the opening of closed facilities. Educational institutions remained closed during the entire LD and UL periods.

In India, the use of public safety measures such as surgical face masks, single-use gloves, hand sanitizer, personal protection equipment kits, tissue papers, and other medical waste generated vast amounts of waste, which affected the environment (Ficetola and Rubolini, 2020) as well as influencing COVID-19 transmission. According to government reports from the months of August 2020 (CPCB, 2020a), September 2020 (CPCB, 2020b), and October 2020 (CPCB, 2020c), India generated about 3025, 4253, 5238, 5490, and 5597 tons of COVID-19 related bio-medical waste in the months of June, July, August, September, and October during 2020, respectively. Moreover, the effects of the COVID-19 pandemic are not uniform and diverse socio-economic groups have been affected differently. Understanding the various consequences of the pandemic on different socio-economic groups is not a simple task (Weston and Frieman, 2020). However, socio-economic groups with a poor economic status are clearly at a greater risk from the spread of the COVID-19 pandemic (van Staden, 2020) in India. In the present study, COVID-19 cases in India were analyzed using geospatial technology during the PLD, LD, and UL phases imposed by the Indian government.

Utilization of geographic information system (GIS) data for understanding the spread of COVID-19 infections

Various mapping techniques have been employed to track and understand the spatial and temporal distributions of many infectious diseases, including cholera, and influenza, and for plague containment (Sarfo and Karuppannan, 2020). GIS is an emerging global health tool for mapping and monitoring the spatial and temporal distributions of infectious diseases. Geographic information can play vital roles in tracking a pandemic, particularly in tasks such as spread identification, prevention and control, allocation of resources, and detecting social sentiment (Pourghasemi et al., 2020; Gatto et al., 2020) and responses during outbreaks (Kamel Boulos and Geraghty, 2020). GIS can allow epidemiologists to map the present and past occurrence of diseases together with many other parameters representing the environment, geography, and demography. These data may help epidemiologists to understand the source of outbreaks as well as the spread pattern and intensity, thereby facilitating the implementation of appropriate disease control, preventive, and surveillance measures (Hellewell et al., 2020; Kamel Boulos and Geraghty, 2020; Murugesan et al., 2020; Papastefanopoulos et al., 2020; Pourghasemi et al., 2020; Rai et al., 2020; Sarfo and Karuppannan, 2020; Zhou et al., 2020). Similarly, policy makers, public health agencies, and administrators can employ GIS tools to understand the overall outbreak patterns in real-time to identify high-risk populations and intervene accordingly by evaluating existing facilities or creating new healthcare infrastructure.

In India, GIS technology is implemented widely and many Web-GIS-based dashboards have been developed for COVID-19 data visualization (Kamel Boulos and Geraghty, 2020; Pourghasemi et al., 2020; Rai et al., 2020; Salgotra et al., 2020). COVID-19 is characterized by large-scale infection, a longer incubation period, and undefined detection, (no specific symptom(s) for detecting COVID-19), thereby resulting in urgent requirements for scientific and technological support to control and prevent the spread of the pandemic (Hellewell et al., 2020; Rahman et al., 2020). During the COVID-19 pandemic, the GIS community developed rapid methods for the visualization of COVID-19 information, spatial tracking of infected cases, and resource planning and management to satisfy basic public needs (Zhou et al., 2020). GIS has been actively used by international bodies such as the WHO as well as academics and

Table 1
Summary of COVID-19 cases in India by October 31, 2020.

Activities	PLD	LD1.0	LD2.0	LD3.0	LD4.0	UL1.0	UL2.0	UL3.0	UL4.0	UL5.0
No. of Tests	22694	222199	862340	1195559	1534415	4989378	10532074	23966175	32294947	34267522
Confirmed Cases	519	9844	29617	50947	91216	384697	1072030	1982375	2604518	1911356
Recovered Cases	40	1325	10398	25032	55067	255978	747698	1741832	2432623	2219433
Deaths	9	330	962	1571	2292	11729	18854	28722	33028	24144
Active Cases	470	8659	26916	51260	85117	202107	507585	719406	858273	526052
Positivity Rate (%)	2.29	4.23	3.61	3.95	4.75	6.42	**8.47**	8.36	8.23	7.40
Recovery Rate (%)	7.71	13.17	29.42	40.47	50.43	61.36	66.85	78.35	84.65	**92.04**
Death Rate (%)	1.73	**3.27**	3.25	3.16	2.84	2.98	2.18	1.78	1.57	1.49
Infection Rate	0.43	8.56	33.02	75.09	150.43	468.13	1353.48	2990.65	5141.63	6720.14

Bold values show the critical values of respective parameter at which remarkable changes had happened.
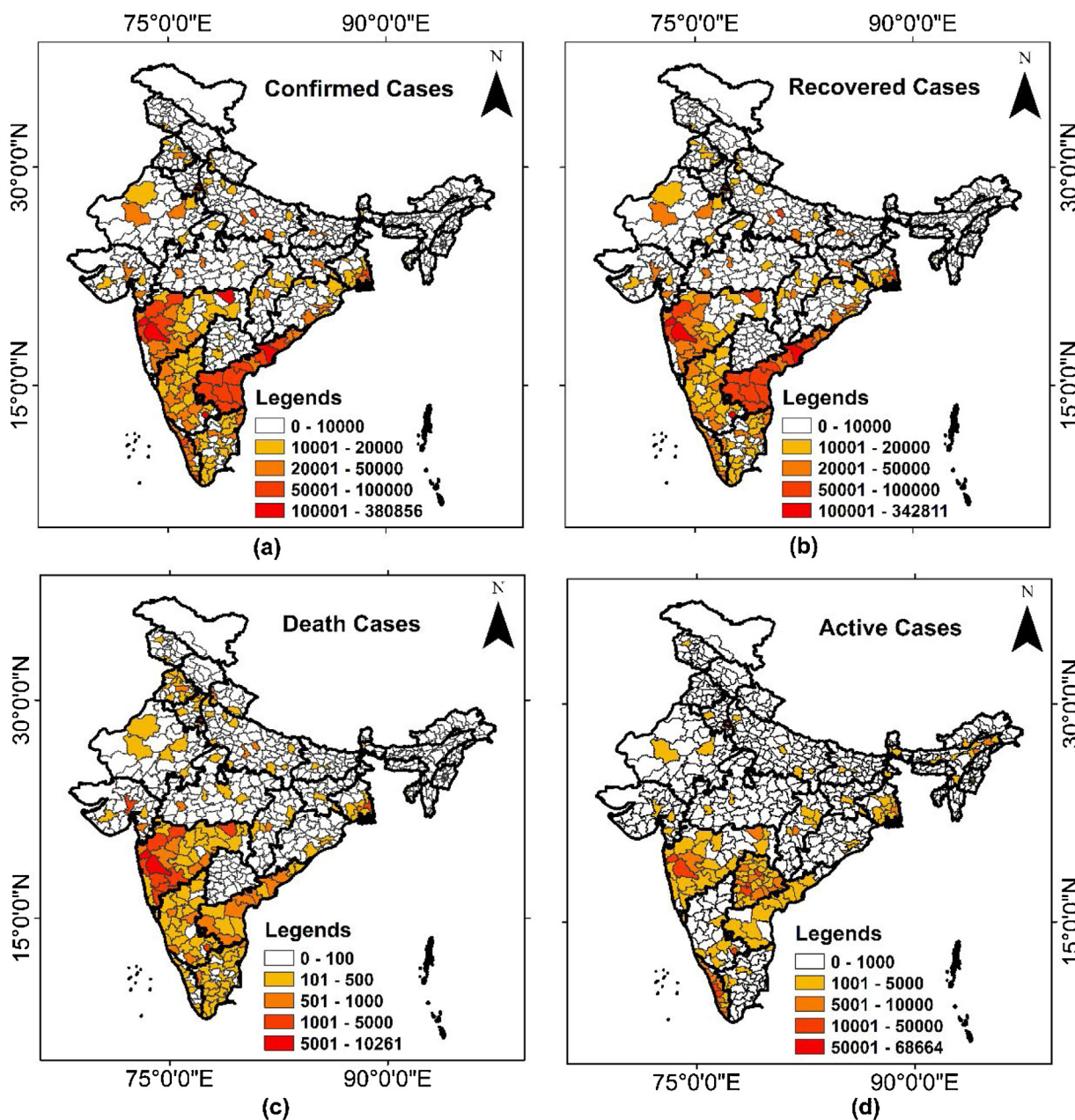

Figure 1. Cumulative COVID-19 cases in the districts of India by October 31, 2020: (a) confirmed cases, (b) recovered cases, (c) deaths, and (d) active cases.

Table 2

Cumulative COVID-19 cases and death rates (%) in India and globally.

Date	Confirmed Cases (India)	Deaths (India)	Confirmed Cases (Global)	Deaths (Global)	Death Rate (India)	Death Rate (Global)
24-03-2020	519	9	411208	17669	1.73	4.30
14-04-2020	10363	339	1879313	122694	**3.27**	6.53
03-05-2020	39980	1301	3374244	246059	3.25	**7.29**
17-05-2020	90927	2872	4557684	309401	3.16	6.79
31-05-2020	182143	5164	5952157	367755	2.84	6.18
30-06-2020	566840	16893	10187633	502322	2.98	4.93
31-07-2020	1638870	35747	17121435	665185	2.18	3.89
31-08-2020	3621245	64469	25167697	846455	1.78	3.36
30-09-2020	6225763	97497	33582480	1007128	1.57	3.00
31-10-2020	8137119	121641	45546031	1188826	1.49	2.61

Bold values show the critical values of respective parameter at which remarkable changes had happened.

local governments for communicating essential information to the public regarding the COVID-19 pandemic. Previous studies have conducted GIS-based disease outbreak, risk, and infection behavior analysis for COVID-19 cases using different mathematical and statistical models (Ficetola and Rubolini, 2020; Gatto et al., 2020; McBryde, 2020; Murugesan et al., 2020; Papastefanopoulos et al., 2020; Pourghasemi et al., 2020; Salgotra et al., 2020; Zhou et al., 2020).

Study region and data sources

India is a part of the Asian continent and it is situated between 8°4' N to 37° 6' N latitude and 68° 7' E to 97° 25' E longitude, with a total population of 1,210,854,977 according to Indian census data from 2011 and a total land area of 3,287,590 km^2. India is the seventh largest country by area throughout the world and the second most populous country. India has a federal structure with 28 states and nine union territories. The major cities in India are Delhi, Mumbai, Chennai, Kolkata, Bengaluru and Hyderabad. Currently, 34 international airports operate in India.

COVID-19 data were collected for diagnosed infected cases and recovered cases, and the total deaths in India during the period from January 30 to October 31, 2020. Daily data for cumulative confirmed, recovered, and death (CRD) cases were obtained from the "covid19india" website
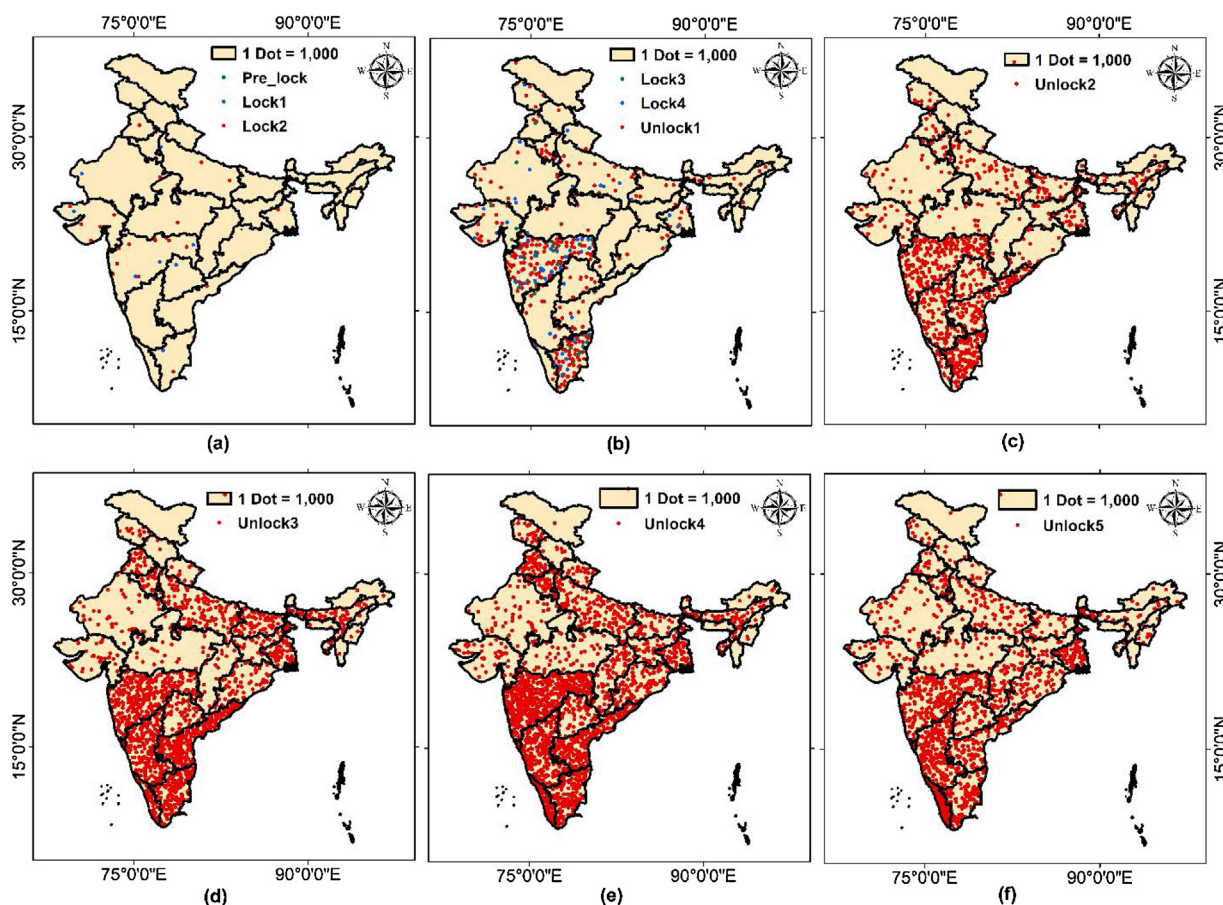

Figure 2. Confirmed COVID-19 cases during PLD, LD, and UL phases.

(https://www.covid19india.org). Census data were obtained from the Office of the Registrar General and Census Commissioner of India, (https://censusindia.gov.in/2011census/population_enumeration.html). Data regarding confirmed and death cases for other countries were downloaded from the WHO coronavirus disease dashboard (https://covid19.who.int/). Other data were collected from peer reviewed research studies on COVID-19 in India and other parts of the world.

(a)

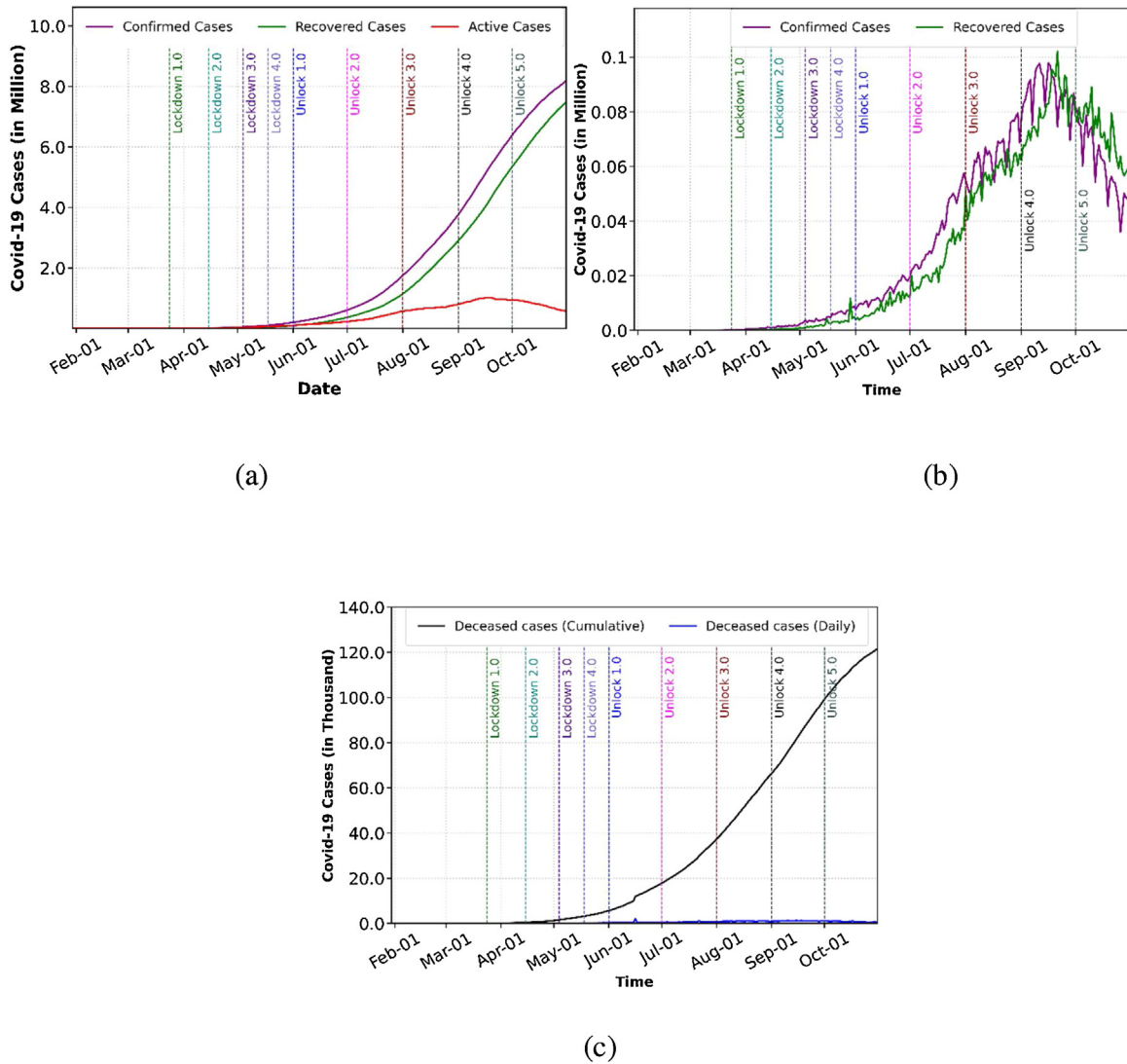(b)

(c)

Figure 3. COVID-19 cases in India during LD and UL phases: (a) cumulative cases, (b) daily cases, and (c) deaths.
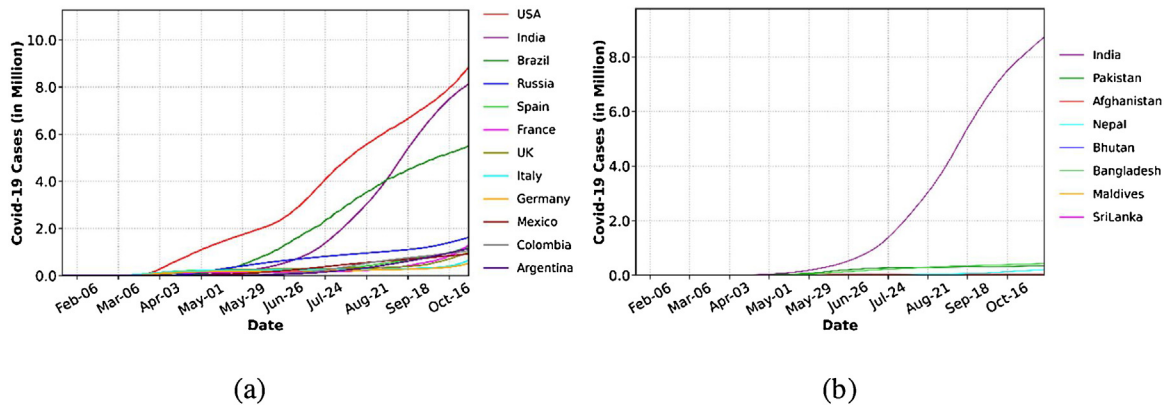

(a)

(b)

Figure 4. Cumulative confirmed cases in the most badly affected countries: (a) selected countries, and (b) SAARC countries.

Results and discussion

The spatial and temporal distributions of COVID-19 infections in India during the PLD and various LD and UL phases imposed by the GoI to fight the COVID-19 pandemic are described in the following.

Current status in India

On October 31, 2020, a total of 2121 operational laboratories reported to the Indian Council of Medical Research for COVID-19 testing in India (ICMR, 2020). Among these 2121 operational laboratories, 1145 laboratories conducted independent RT-PCR testing, 848 laboratories were authorized for the TrueNat Test, and 128 laboratories conducted the CBNAAT Test for COVID-19 (ICMR, 2020).

The total number of confirmed COVID-19 cases in India exceeded 8.1 million by October 31, 2020. Table 1 shows the numbers of COVID-19 cases in India during the PLD, LD, and UL phases.

The number of COVID-19 tests increased from the PLD to UL5.0 phases, and the number of CRD cases increased from the PLD to UL4.0 phases but decreased in the UL5.0 phase. The positivity rate was highest in UL2.0 and it decreased subsequently in UL3.0–UL5.0. The recovery rate was lowest in the PLD period but it then increased to 92.04% in the UL5.0 phase. Initially, the death rate was 1.73% in the PLD period and it then reached a maximum of 3.27% in LD1.0, before decreasing to 1.49% in UL5.0. No declines occurred in the number of infected persons per million population

(infection rate), even in UL5.0, which is a highly alarming situation for India.

Figure 1 shows the cumulative COVID-19 cases in the districts of India by October 31, 2020. The highly infected districts were in the southern, eastern, and west–central parts of the country. By October 31, 2020, 8,137,119 confirmed cases (17.87% of global infections), 7,489,426 recovered cases, 121,641 deaths (10.23% of global deaths), and 526,052 active cases had been recorded in India.

Delhi, Mumbai, Chennai, Kolkata, Hyderabad, and Bengaluru recorded the highest numbers of cumulative confirmed cases per unit area, and the maximum recoveries per unit area were reported in DL, Mumbai, Chennai, Kolkata, Bengaluru, and Chandigarh. By the same date, Mumbai, DL, Kolkata, Chennai, Chandigarh, and Bengaluru had recorded the most deaths, and Hyderabad, DL, Mumbai, Kolkata Chennai, and Kamrup Metropolitan had the highest numbers of active cases per unit area.

The spatial distributions of the cumulative confirmed, recovered, death, and active (CRDA) cases in the states of India were also analyzed. At the end of UL5.0, Maharashtra (MH) followed by Karnataka (KA), Andhra Pradesh (AP), Tamil Nadu (TN), and Uttar Pradesh (UP) states had the highest numbers of cumulative confirmed cases (55.38% of the total cases), and MH followed by AP, KA, TN, and UP had the largest numbers of recovered cases (56.1% of total recoveries). The maximum numbers of deaths were reported in MH, KA, TN, UP, and West Bengal (WB) (65.55% of total deaths), and the highest number of active cases are recorded in MH, Kerala (KL), KA, WB, and Delhi (59.55% of total active cases).
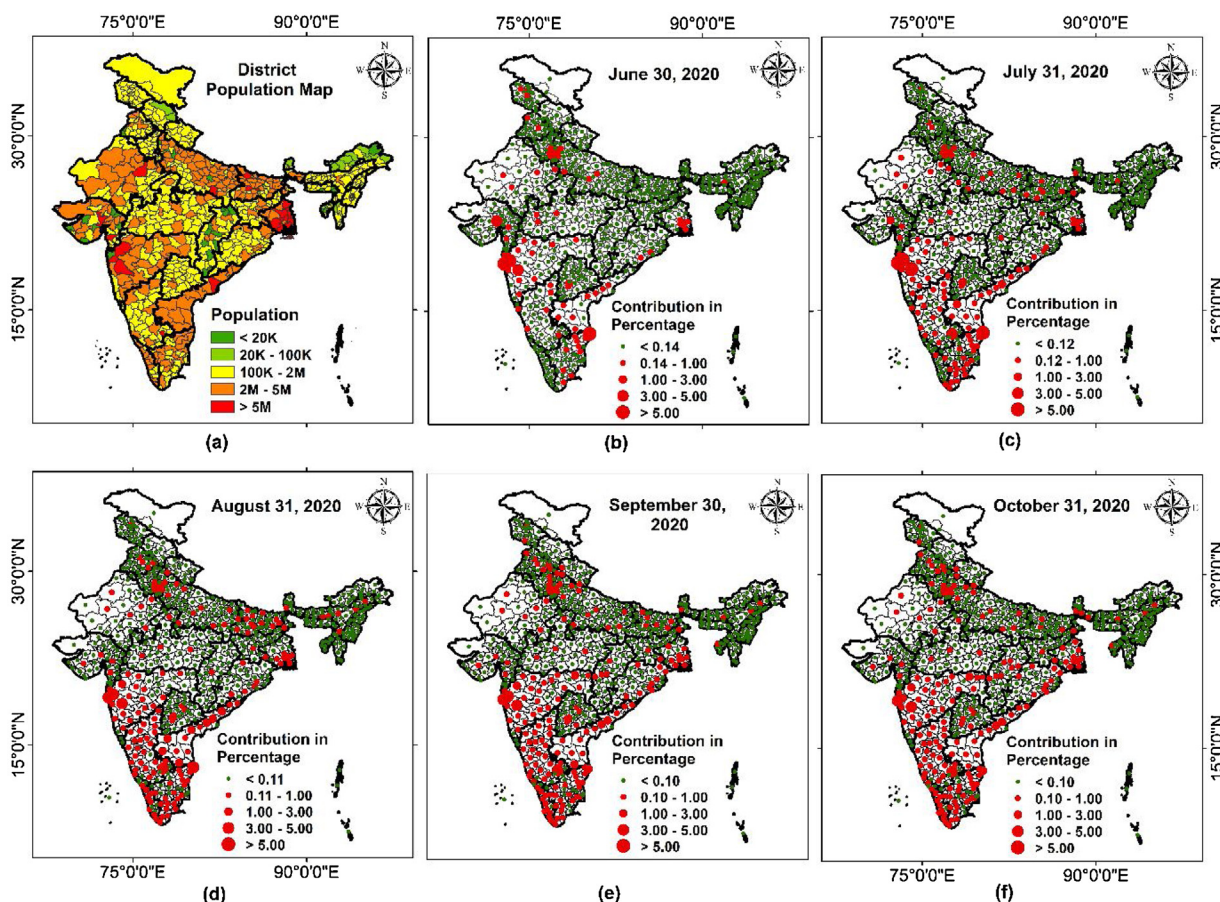

Figure 5. Classifications and distributions of cumulative confirmed COVID-19 cases, where the total of the red dots represents 80% of the cases in a district.

The cumulative confirmed cases, deaths, and death rates in India are compared with the global values at the end of the PLD, LD, and UL phases in Table 2. The death rate in India was lower than the global average during the entire study period. The highest death rate was 3.27% in India during the middle of April 2020, but the highest average global death rate was 7.30% (Table 2) at the start of May 2020.

COVID-19 situation in India during PLD, LD and UL phases

The total CRD cases due to the COVID-19 pandemic in India during the PLD, LD, and UL phases are shown in Table 2 and Figure 3. Figure 2 shows the spatio-temporal distribution of confirmed cases in the states of India. In the PLD period, the highest case numbers were reported in KL followed by MH, KA, Telangana (TG), and UP. The numbers of confirmed cases increased (Figure 2) in almost all states during the LD phases. The top five states (in chronological order) with the highest numbers of confirmed cases in each of the LD phases were: (1) LD1.0: MH with 2537 cases and acted like a epicenter, followed by DL, TN, Rajasthan (RJ), and Madhya Pradesh (MP); (2) LD2.0: MH, Gujarat (GJ), DL, MP, and UP; (3) LD3.0: MH, TN, GJ, DL, and RJ; and (4) LD4.0: MH, TN, DL, GJ, and RJ.

A rapid spatial spread of confirmed COVID-19 cases was observed in MH, TN, and DL during UL1.0 (Figure 2(b)), and it continued in other states such as KL, AP, and KA in the south, Punjab (PB) and UP in the north, and WB, Odisha (OD), and Bihar (BR) in the east until UL4.0 (Figure 2(c), (d), and (e)). Figure 2(f) shows that slight decreases in the numbers of confirmed cases

occurred during UL5.0 in all states. Infections increased rapidly due to the relaxation of interstate movements and the opening of market shops, business offices, industries, religious places, etc. Rapid increases in COVID-19 cases were observed in areas with high population densities, poor testing facilities without frequent and adequate testing, and changes in human behavior due to various reasons. The top five states with the maximum numbers of cases in all UL phases were: (1) UL1.0: MH, TN, DL, GJ, and UP; (2) UL2.0: MH, TN, AP, KA, and UP; (3) UL3.0: MH, AP, KA, TN, and UP; (4) UL4.0: MH, KA, AP, TN, and UP; and (5) UL5.0: MH, KL, KA, AP, and TN. MH was the epicenter for COVID-19 infections in India and the first reported confirmed cases occurred in this state during all LD and UL phases. Due to the efforts of the GoI, many testing sites were distributed evenly across states irrespective of the population density and healthcare facilities, and thus the infection rates and rate of spread could have been lower in the Indian states, as reflected in UL5.0.

Figure 3 shows the spread of COVID-19 where the infection rate was lower during the LD phases (LD1.0–LD4.0) but it increased significantly after the start of the UL phase on June 1, 2020. Overall mobility was restricted during the LD phases, before it was relaxed in a phased manner during the UL period. Thus, the measures implemented in different regions during LD to restrict movement helped to limit the infection rates. Figure 3(a), (b), and (c) show the cumulative (confirmed, recovered, and active) cases, daily confirmed and recovered cases, and deaths (cumulative and daily) in India, respectively. The daily reported cases peaked during the middle of UL4.0 phase and reached their lowest level in UL5.0 phase.
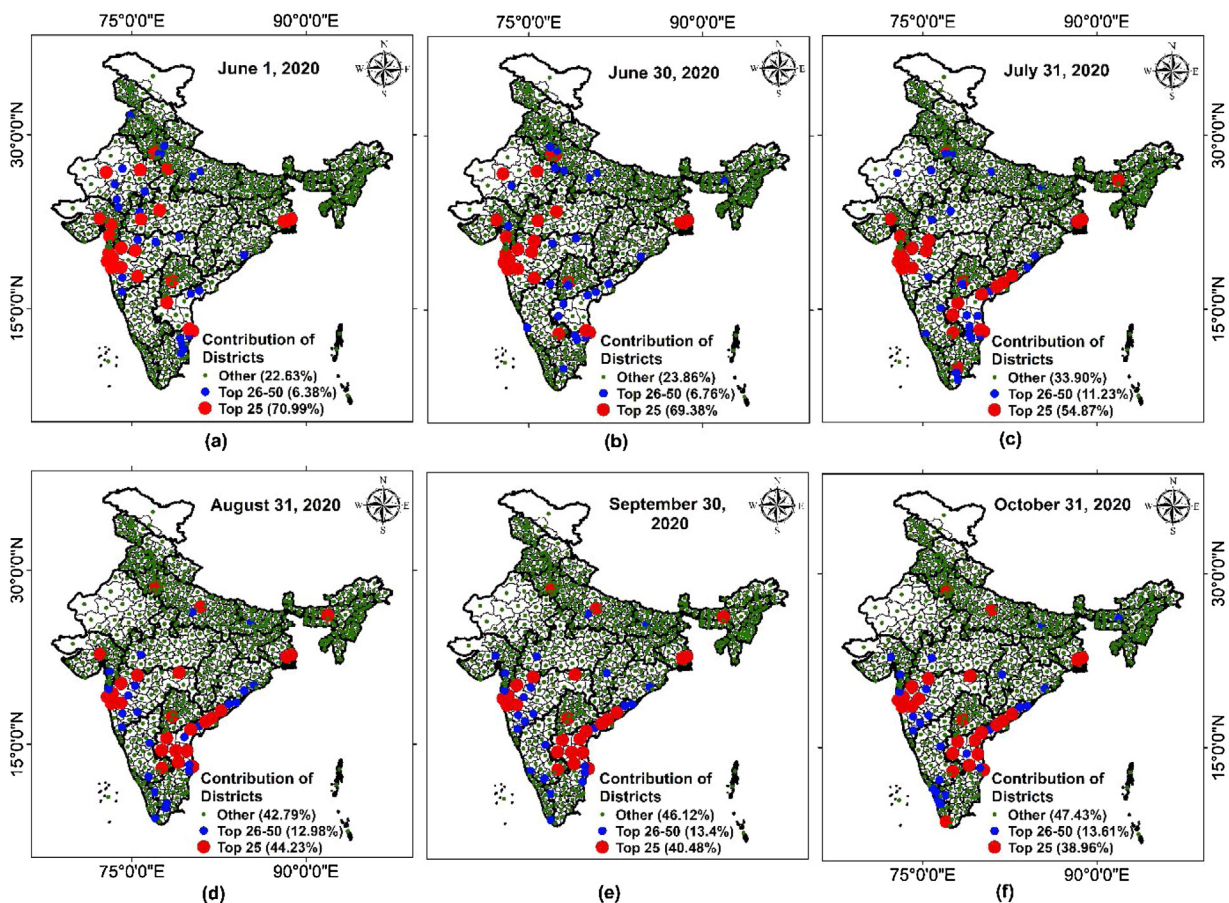

Figure 6. Percentage contributions of top 25 districts, top 26–50 districts, and remaining districts to confirmed cases.
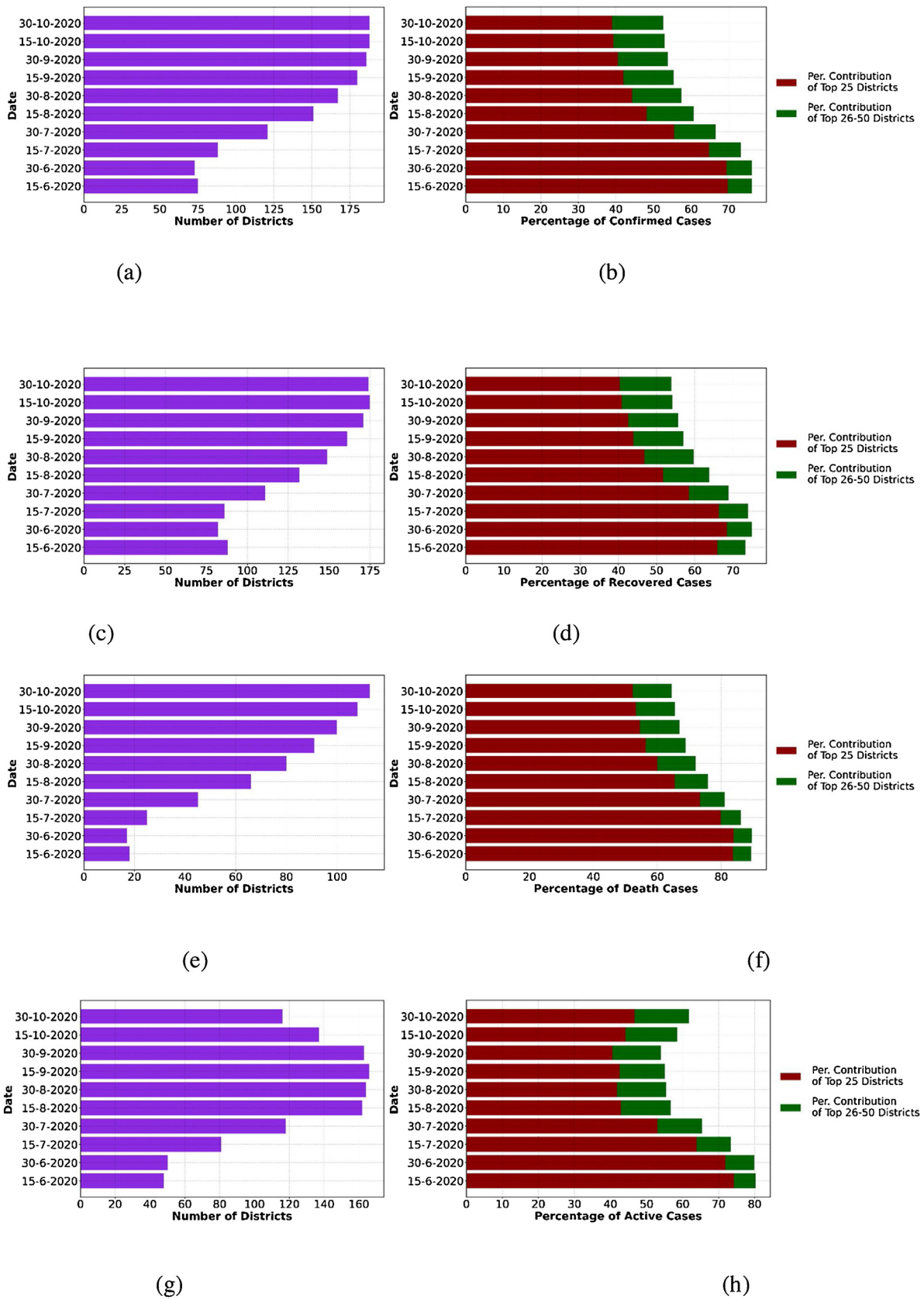
Figure 7. Contributions of top districts to COVID-19 confirmed, recovered, death, and active cases over 15-day intervals: (a), (c), (e), and (g) number of districts that accounted for 80% of total CRDA cases, respectively; (b), (d), (f), and (h) percentage contributions of top districts to CRDA cases, respectively.
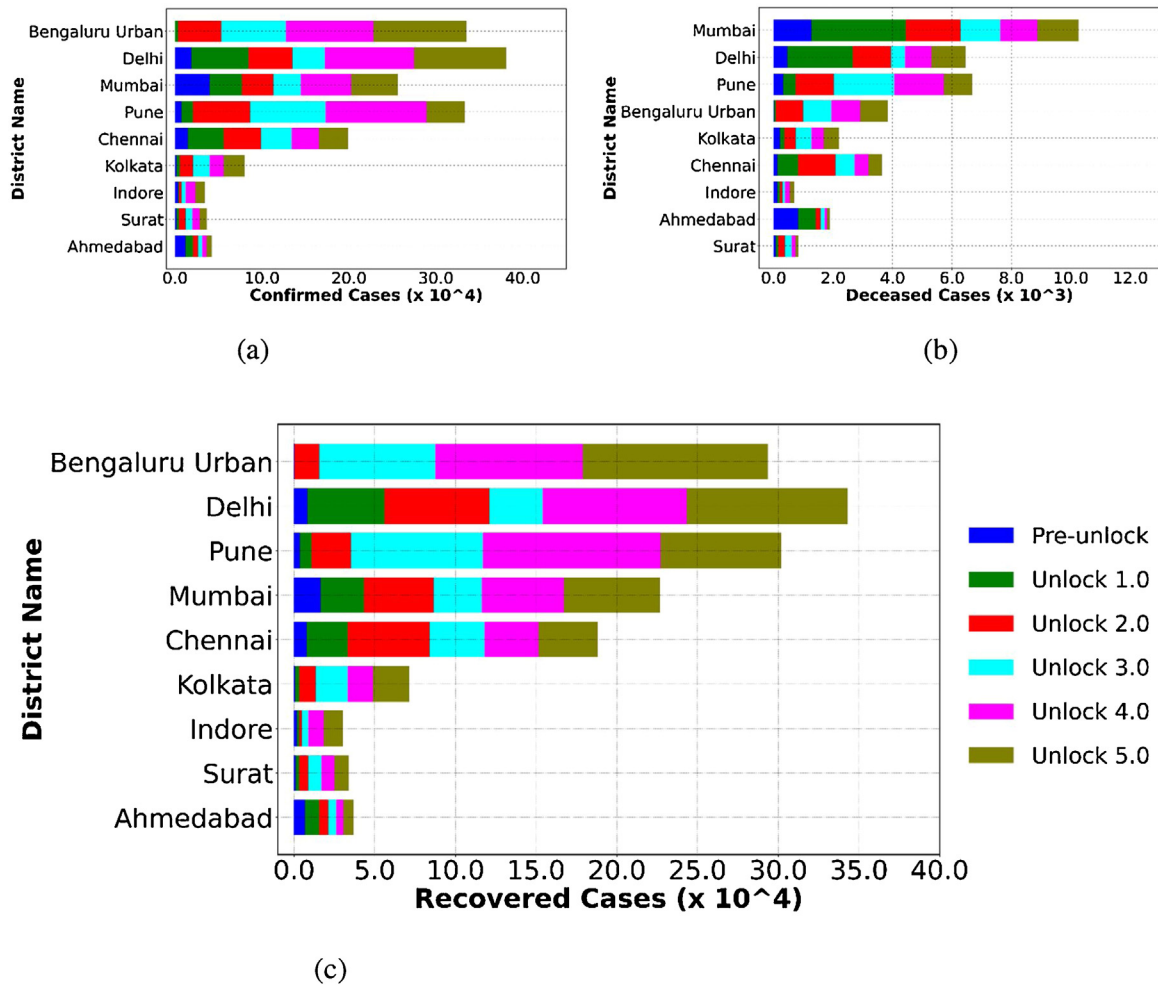
Figure 8. COVID-19 cases in selected districts of India during UL phases: (a) confirmed cases, (b) deaths, and (c) recovered cases.
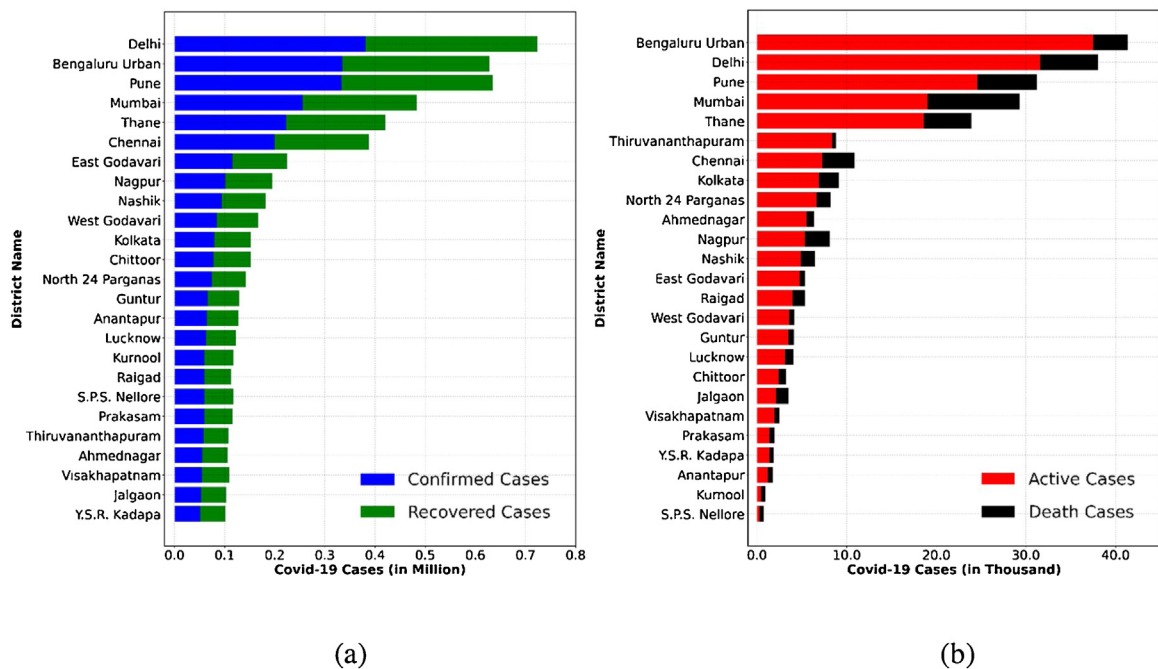

Figure 9. Top 25 districts in India in terms of confirmed COVID-19 cases by October 31, 2020: (a) confirmed and recovered cases, and (b) active cases and deaths.

Comparison of COVID-19 in India with selected countries across the world and South Asian Association for Regional Cooperation (SAARC) countries

The total confirmed COVID-19 cases in India were compared with those in the most affected countries throughout the world as well as in SAARC countries. Figure 4(a) shows that India was the third most badly affected country in the word after the USA and Brazil during the UL2.0 and UL3.0 periods, and the second most badly affected after the USA during UL4.0 and UL5.0. India was the most badly affected among the SAARC countries during the entire study period (Figure 4(b)).

Classification and distribution of 80% of confirmed cases

The infection spread rate was not uniform throughout India during the entire pandemic period. The maximum infection rates were concentrated around high population density areas. Figure 5(a) shows a population map of the districts of India, with the very high population areas in MH, WB, AP, DL, UP, and BR. Confirmed COVID-19 cases were classified at the end of each phase based on the percentage contribution of each district in the whole country. The totals of the red dots in Figure 5(b)–(f) represent 80%

of the confirmed cases in a district, which indicate that uniform government control was not required in all districts. In order to save resources and control the spread of the pandemic in a timely manner, the government focused on the locations that comprised 80% of the cases. At the end of UL1.0, the number of these locations was low with 74 districts but it subsequently increased at the end of UL2.0–123 districts, and then to 168 locations in UL3.0, 187 districts in UL4.0, and 189 districts in UL5.0, as shown in Figure 7(a). Figure 5 indicates that the distribution of the districts that contributed 80% of the cases was greater in the most populous regions of the country.

Percentage contributions of Top 25 and Top 26–50 infected districts

The results also showed that only a few districts accounted for most of the total confirmed cases in India. The percentage contributions of the top 25 districts, top 26–50 districts, and remaining 677 districts in different time periods are shown in Figure 6. On June 1, 2020 immediately after the LD4.0 period, 70.99% of the confirmed cases occurred in the top 25 districts, 6.38% of confirmed cases in the top 26–50 districts, and only 22.63% of the confirmed cases in the remaining 677 districts. After the UL started, the contributions of the top 25 districts decreased,
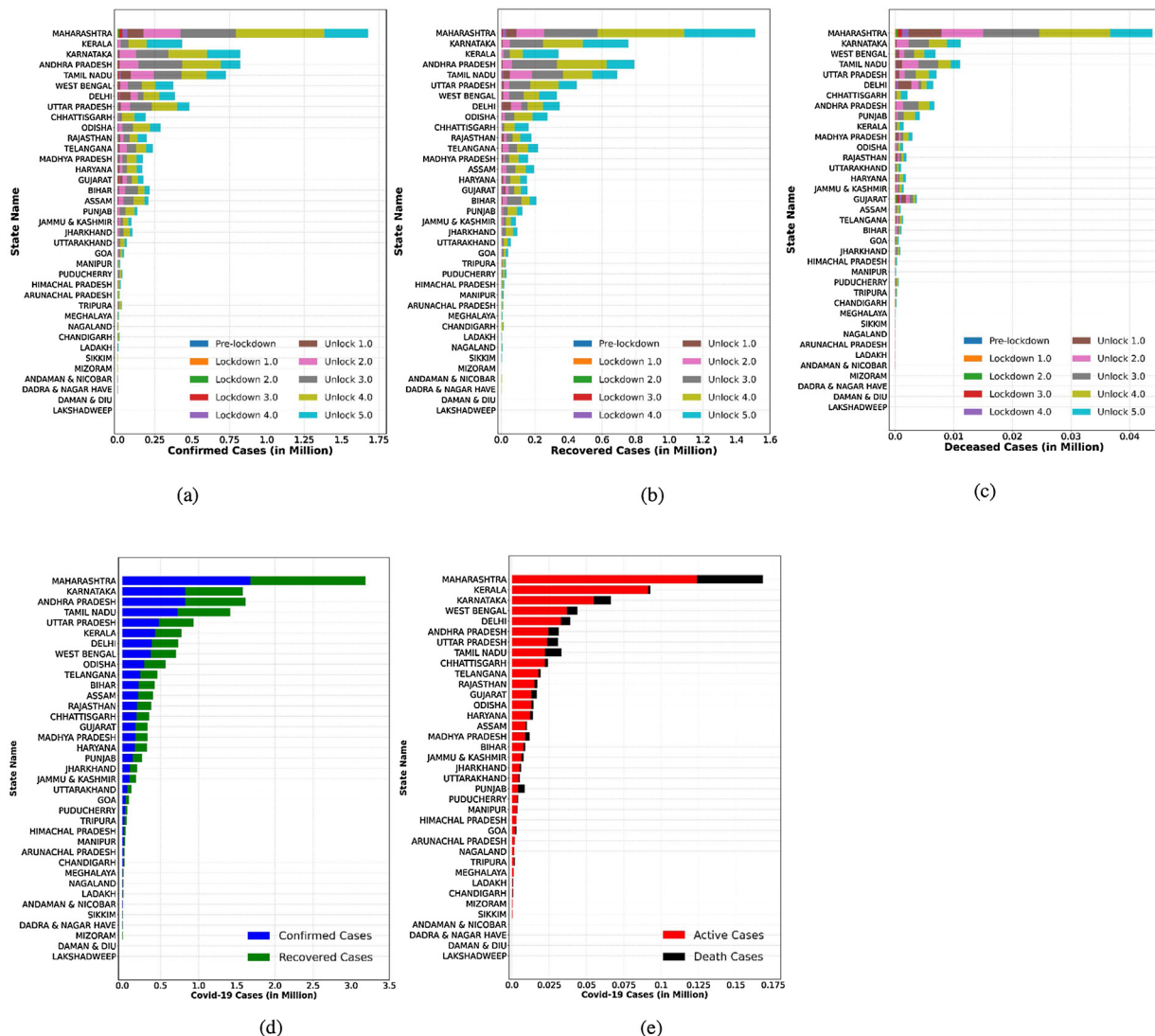

(a) (b) (c)

(d) (e)

Figure 10. COVID-19 cases in Indian states: (a) confirmed cases during PLD, LD, and UL phases; (b) recovered cases during PLD, LD, and UL phases; (c) deaths during PLD, LD, and UL phases, (d) confirmed and recovered cases by October 31, 2020; and (e) active cases and deaths by October 31, 2020.

whereas those of the top 26–50 districts increased slowly and those of the remaining districts increased rapidly, thereby clearly demonstrating that the spread of COVID-19 cases increased during the UL period, as shown in Figures 6 and 7 (b).

Figure 7 shows the number of districts that accounted for 80% of CRDA cases, as well as the percentage contributions of the top 25 districts and top 26–50 districts in India to CRDA cases at 15-day intervals. The number of districts that accounted for 80% of CRD cases increased in the UL phases (Figure 7(a), (c), and (e)), whereas the number of active cases increased until the middle of UL4.0 and then decreased (Figure 7(g)). The percentage contributions of CRD cases (Figure 7(b), (d), and (f)) by the top 25 districts and top 26–50 districts were highest in UL1.0 before they then decreased, thereby demonstrating the greater spatial spread of CRD cases in the remaining districts. The contribution of the top 25 districts to active cases (Figure 7(h)) was around 74% in UL1.0 but it then decreased to 41% at the end of UL4.0, before increasing again in UL5.0. The decrease in the number of districts that accounted for 80% of active cases and the increase in the contribution from the top 25 districts at the end of UL5.0 show that the recovery rate was very high in other districts.

COVID-19 cases in selected districts

Throughout the LD and UL phases, the maximum numbers of cases were reported for only a few major cities in India. Figure 8 shows the confirmed, death, and recovered cases at the start of UL1.0 and during each UL phase in major Indian cities. During UL5.0, Bengaluru Urban had the highest number of confirmed cases (Figure 8(a)) and highest number of recovered cases (Figure 8(c)), whereas Mumbai had the lowest maximum number of COVID-19 infected persons (Figure 8(b)).

Figure 9 shows the numbers of COVID-19 CRDA cases in the top 25 districts at the end of UL5.0. DL had the most confirmed cases followed by Bengaluru Urban, Pune, Mumbai, Thane, and Chennai.

COVID-19 cases in Indian states

The COVID-19 CRD cases in Indian states during the PLD, LD, and UL phases, as well as the CRDA cases at the end of UL5.0 are shown in Figure 10. The total numbers of CRD cases were highest in MH during the PLD, LD, and UL phases, mainly because major cities such as Mumbai, Pune, Thane, Nagpur, and Nashik are located in this state. At the end of UL5.0, MH still had the most CRDA cases compared with other states, as shown in Figure 10(d) and (e).

Conclusions

In this study, geospatial analysis was conducted to assess COVID-19 CRDA cases in India during the PLD, LD, and UL phases. Analyses were performed at the country, state, and district levels, and Indian COVID-19 cases were also compared with those in the other most infected countries throughout the world. The death rate in India was lower than the global average throughout the pandemic period considered. India was the third most badly affected country throughout the world after the USA and Brazil during the UL2.0 and UL3.0 periods, and the second most badly affected after the USA during UL4.0 and UL5.0. India was the most badly affected of SAARC countries from the start of the pandemic until UL5.0. In India, the highest positivity rate was 8.47% in UL2.0, the highest death rate was 3.27% in LD1.0, and the highest recovery rate was 92.04% in UL5.0. The total daily numbers of confirmed and recovered cases in India peaked during the middle of UL4.0, before subsequently decreasing until the end of UL5.0.

The spatial distributions of confirmed cases in Indian states were mapped during the PLD, LD, and UL phases. The numbers of confirmed cases increased in all states from PLD to UL4.0, but decreased slightly in UL5.0. The maximum number of confirmed cases during PLD occurred in KL, and the highest numbers of confirmed cases during all LD and UL phases were recorded in MH. Major increases in COVID-19 cases during UL1.0–UL4.0 were observed in the west–central part comprising MH, southern states of KL, TN, AP, and KA, northern states of Delhi, PB, and UP, and eastern states of WB, OD, and BR.

The observed infection spread rate was not uniform throughout the country during the entire pandemic period considered. Classifications of confirmed cases at the end of each UL phase based on the percentage contribution of each district in the whole country showed that 80% of the confirmed cases occurred in a few high population areas, i.e., MH, AP, TN, KA, KL, GJ, DL, UP, BR, WB, and OD. This spatial distribution could facilitate decision making when controlling the spread of COVID-19. The results showed that among 727 districts in India, 80% of the confirmed cases occurred in only 74, 123, 168, 187, and 189 districts at the end of each UL period, respectively. UL1.0: June 1-30, 2020, UL2.0: July 1-31, 2020, UL3.0: August 1-31, 2020, UL4.0: September 1-30, 2020, UL5.0: October 1-31, 2020. In addition, the contributions of the top 25 districts, top 26–50 districts, and remaining districts to CRDA cases were assessed. The top 25 districts accounted for 70.99%, 69.38%, 54.87%, 44.23%, 40.48%, and 38.96% of cases at the start of UL1.0 and at the ends of UL1.0–UL5.0, respectively, and the top 26–50 districts accounted for 6.38%, 6.76%, 11.23%, 12.98%, 13.40%, and 13.61%. Clearly, the contributions of the top 25 districts decreased when UL started, whereas those of the top 26–50 districts increased slowly and those of the remaining districts increased rapidly, thereby indicating the greater spread of COVID-19 cases in India during the UL phases. Moreover, the top 25 districts accounted for around 74% of the active cases in UL1.0, before decreasing to 41% at the end of UL4.0 and then increasing again in UL5.0. By October 31, 2020, DL had the highest number of confirmed cases in India followed by Bengaluru Urban, Pune, Mumbai, Thane, and Chennai.

Conflict of interest

This is to inform you that the proposed reviewers have no conflicts of interest to declare and they agreed to review this manuscript. 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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Ethical statement

The instructions to the authors have been read and accepted by all the authors of this manuscript. All of the authors have seen the manuscript and agreed to the submission of this version. The research described in this paper is manuscript and it has not been published or submitted for publication in any other journal simultaneously. We also agree that if this paper is accepted for publication, the paper will not be published elsewhere in the same form in English or any other language without the written consent of the copyright holder.

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