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Research Article

Modelling and Forecasting COVID-19 Transmission Dynamics: A Susceptible-Infected-Recovered (SIR)-based Approach for Informed Decision-Making

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ABSTRACT

Background: The global pandemic scenario of COVID-19 disease cases has made it extremely difficult for emerging scientific research to anticipate outbreaks. To accurately anticipate the predictions, more and more epidemiological mathematical models of spread are being developed daily. The traditional Susceptible-Infected-Recovered (SIR) modelling methodology was used in this research to predict the outcomes of future pandemics and the importance of interventions to end the pandemic.

Methods: A traditional SIR model was applied to forecast the time trends of upcoming pandemics in India. The data were obtained from the Indian Council of Medical Research (ICMR) from March 2020 to June 2022, for a total period of 801 days. The SIR model was constructed using the Python functioning and parameters were estimated.

Results: The SIR model for COVID-19 confirmed that preventive strategies would change the basic reproductive number, in a way that the pandemic can be contained with less morbidity and mortality. The R_0 value of SARS-CoV-2 varies in the presence of interventions and in their absence from 2.89 to 1.92.

Conclusion: Using the SIR model for infectious diseases, it was understood that the natural progression of the disease can become quite dangerous without government interventions, and so policy changes need to be implemented quickly to flatten the epidemic curve.

Keywords: SIR Model, COVID-19, Pandemic, Epidemiological Modelling, Basic Reproductive Number, Epidemic Curve

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Introduction

With millions of victims worldwide, the COVID-19 pandemic has been one of the most important global health crises in recent memory. The pandemic has had a particularly negative effect on India, where infection and mortality rates are both high. It is imperative to comprehend the pandemic's impact and predict any possible future waves as COVID-19 continues to change.[1] Understanding the dynamics of this pandemic became vital in order to mitigate the loss of human life in case of future pandemics. The forecast of COVID-19 in a big country like India can help us in seeking answers to the various geopolitical and financial issues that burdened our country during the pandemic.[2] It will also help us to identify whether the preventive measures undertaken by the government have helped us to overcome this pandemic, and will hopefully help us to be prepared for future pandemics.

Epidemic models are instruments that are frequently used to research the mechanisms of disease transmission, forecast the trajectory of an outbreak, and assess control measures.[3] Various epidemiological and mathematical models have predicted the end of the pandemic, and the positive outcome of the detailed measures taken by the government such as lockdown, quarantine, screening, diagnosing and putting dedicated COVID-19 hospitals, increasing sample testing etc.[4]

The findings of this study will offer significant new information about the COVID-19 pandemic in India, assisting decision-makers in public health and policy-making to control the spread of the virus and lessen its effects on the populace. Additionally, the results of this research can assist international efforts to combat the COVID-19 pandemic and future outbreaks of similar infectious diseases.

Methodology

Using data-driven methodologies to comprehend the patterns and trends of the disease, this study seeks to provide a thorough analysis of the COVID-19 pandemic in India. We used the classic SIR model to predict the time trends of future pandemics, assuming similar interventions and similar transmission rates in our country.[5] The research involves secondary data analysis of epidemiological data received from the Indian Council of Medical Research (ICMR) were collected till June 2022, from the date of the first case detected in each state. The total duration during which the data were obtained was 801 days. The data were filtered and any incomplete data were excluded from analysis. The simulations of the SIR model were performed using fminsearch and ode45 functions of SIGMA XL version 9, with Python log functioning.

SIR Model

The population was split into three distinct categories according to the Susceptible-Infected-Removed (SIR) compartmental model of infectious disease dynamics. The term "susceptible" (S) designated a group of individuals who had never contracted the disease but were susceptible to doing so. The group of individuals who had the infection and could spread it is referred to as being infected (I). Those who had either recovered from the illness or had passed away from it and were no longer able to spread the disease are referred to as removed (R).

This model is defined by these three differential equations:

N (Total population) = $S + I + R$,

$dS/dt = -\beta SI$,

$dI/dt = \beta SI - \gamma I$,

and $dR/dt = \gamma I$

where, t is time, S(t) is the number of susceptible persons at time t, I(t) is the number of infected persons at time t, and R(t) is the number of recovered persons at time t. Beta (β) is the transmission rate, and 1/γ is the average infectious period.[6] During the course of three phases of COVID-19 (T1, T2 and T3), there were two significant peaks of infections seen because of Omicron and Delta strains (Figure 1). The reasons attributed were relaxing the policy changes in restricting movement and thereby increasing contact rates. t_{max} is the time period at which the highest peak of infections was seen.

T1 phase (Alpha strain): March 2020 to December 2020 (peak fractions of infected individuals (t_{max}) were observed in September 2020)

T2 phase (Delta strain): January 2021 to September 2021 (t_{max} was observed in the month of April–May 2021)

T3 phase (Omicron strain): October 2021 to June 2022 (t_{max} was seen in January–February 2022)

SIR assumes a homogeneous and constant population, and it is fully defined by the parameters β (transmission rate) and γ (recovery rate). The assumption behind this model was that every infected patient gets in contact with β (average contact frequency) people. It was important to calculate the basic reproduction number (R_0) of the viral pandemic to understand the disease dynamics. In our study, we used COVID-19 datasets from the ICMR data in the form of time series, spanning March 2020 to June 2022. It can be calculated using contact-tracing data, but the most common method was to use cumulative incidence data.

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$R_0 = \beta/\gamma$

R_0 was dependent on the strain and policy changes during the course of the pandemic. Estimation of I_{max} (percentage infected persons at the peak of the epidemic) and S_{inf} (percentage of susceptible people remaining after the end of the epidemic) was done for the pandemic model, considering both scenarios, with and without policy implementation.[7] Policy implementations included all the preventive strategies like lockdown, quarantine, rapid and extensive screening, and immediate treatment of suspected cases etc., that were tried during the COVID-19 pandemic and proved to be effective.

Results

The SIR model was derived using the log statistics after determining the transmission and recovery rates of the SARS-CoV-2 virus. Figure 2 shows that in case of the natural progression of the disease in the absence of any preventive strategies to contain the pandemic, the R_0 of the disease would stay high, and the pandemic would die quickly but with higher mortality and morbidity. The number of infected individuals would peak quickly, S_{inf} would be around 70.3%, and the others might develop natural or herd immunity. The transmission and recovery rates were determined at 0.08 and 0.04 respectively ($\beta = 0.0816$, $\gamma = 0.0424$, and $R_0 = 1.92$).

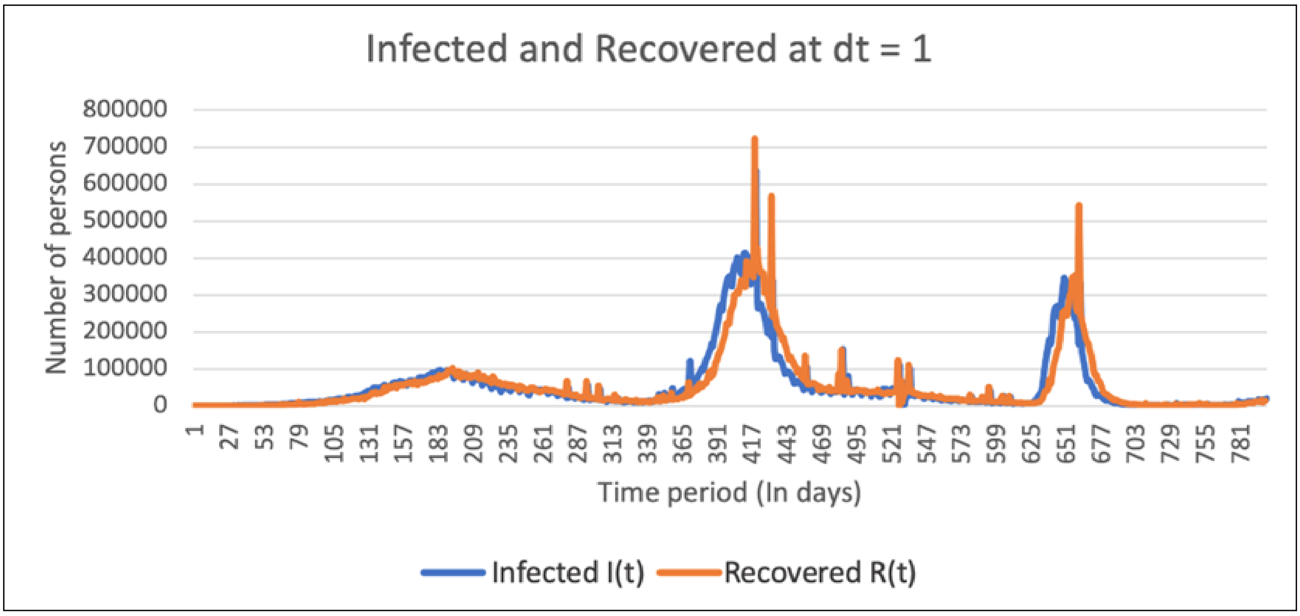

Figure 1.Frequency of Infections and Recoveries

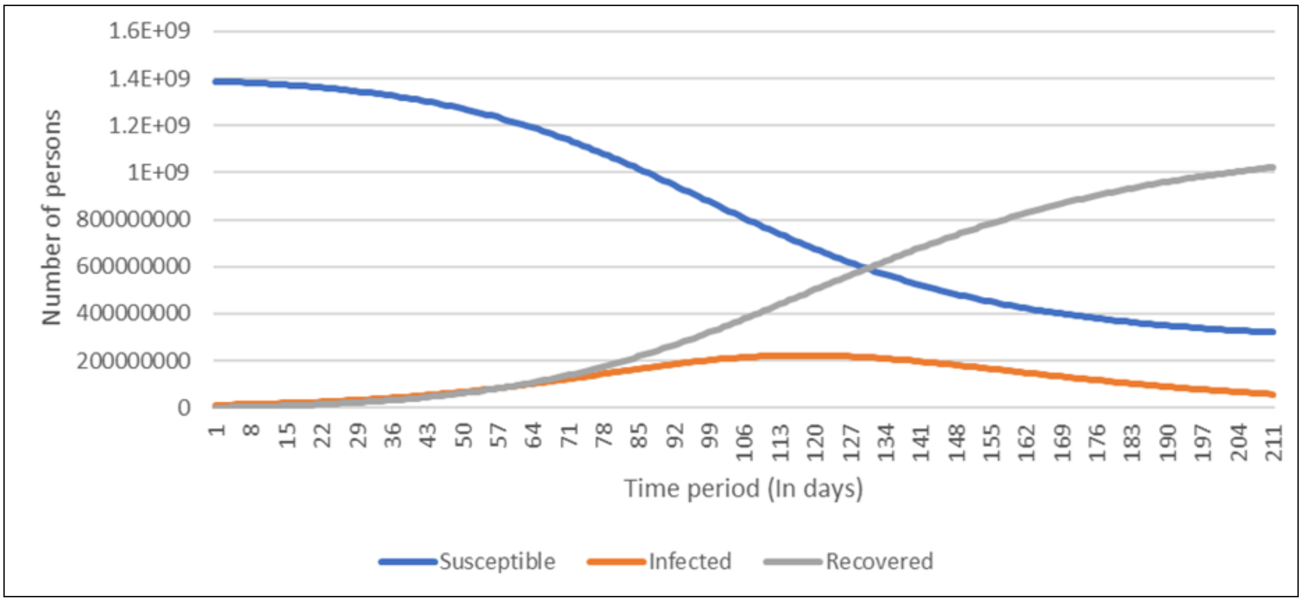

Figure 2.Predicted SIR Model for Future Pandemics in the Absence of Preventive Strategies (tmax = 130, imax = 23.2%, Sinf = 70.3%,)

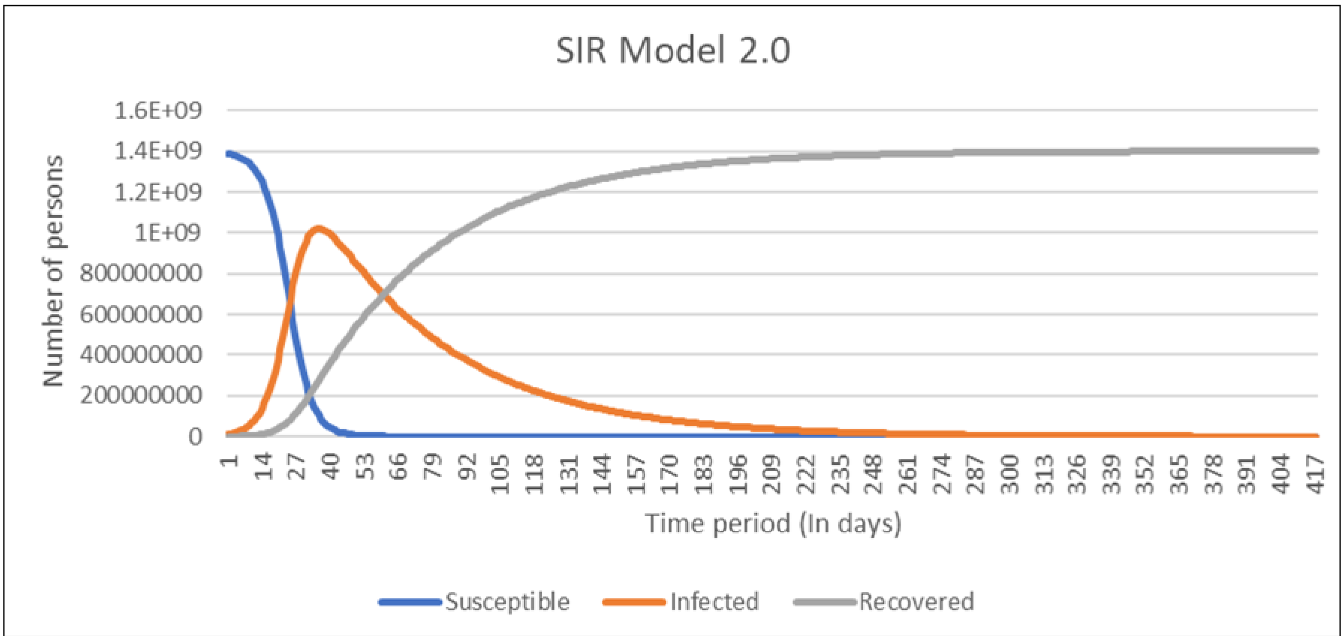

Figure 3.Predicted SIR Model for Future Pandemics with Policy Implementations (tmax = 49.5, imax = 71.6%, Sinf = 90.08%)

From the observations in Figure 3, it is understood that having the lockdown procedures in place soon after the epidemic would result in peak infections quickly (t_{max} = 50 days after the first case). The infections would also fall rapidly and the recovery of cases would rise quickly. The susceptible population after the infection would be higher (90%), due to the lower recovery rate determined in this case. The infections would peak at 71.6% of the population, but it has to be noted that the time at which this would happen is quite sooner, and would be associated with a rapid fall, rather than a slow rise and slow fall compared to the model that is designed with a lack of preventive strategies (β = 0.217, γ = 0.075, and R_0 = 2.89).

By using the basic reproductive value, the proportion of people who need to be immune or vaccinated to achieve herd immunity can be calculated using the following formula:

$N_I = 1-1/R_0$

Without policy implementations, not taking into account the time required for immunising the population, it was estimated that 49% of the people need to be immunised naturally to achieve herd immunity, but with policy implementations, 65% of the population needs to be vaccinated to end the pandemic.

Discussion

The SIR model used in this study has found a high basic reproductive number in COVID-19, indicating the pandemic potential of the virus, but these estimated basic reproduction number values could vary slightly from the real-world data. This is a result of the model's underlying assumptions that the susceptible count is equal to the community as a whole and that the effective contact rate and the recovery rate are constant.[7]

The flattening of the curve, which refers to ending the pandemic results in (i) a decrease in the peak number of cases, preventing the health system from becoming overburdened, and (ii) an extension of the pandemic with the same overall load of cases. This suggests that social distancing practises and case management, with their devastating effects on the economy and society, may need to persist for a lot longer.[8] Chae et al. worked out a SIQR model for COVID-19 in South Korea, which showed that the infections peaked at around 50 days when the government enforced quarantine. According to their model, they estimated 6 months to eradicate the disease. They observed that the asymptomatic recovered population increased after six months.[9]

Lounis and Bagal estimated the parameters of the SIR model for COVID-19 in Algeria, like the reproduction number (R_0), which was calculated to be 1.232. With the epidemic curve, they were able to predict that t_{max} would be reached after 561 days, and the S_{inf} for Algeria was 35.23%. Their R_0 was lower than the value that we have obtained, which could be due to differences in population density among the countries.[10]

In our study, for two different scenarios, some assumptions were taken into account in the Python simulation to suit the model. In each scenario in India, the SIR model's predicted parameters showed signs of progress. Similarly, Bagal et al. have done a SIR model for all lockdown scenarios in India and have suggested that in the near future, extreme interventions should be carried out to address this kind of pandemic situation. Their study on the parameters of the model showed that the recovery rate increased and the transmission rate decreased with the betterment of each lockdown measure. The R_0 value also gradually decreased flattening the epidemic curve, and so they pointed out that strict government interventions were needed to curb the pandemic.[11]

Conclusion

COVID-19, being complex and unpredictable, with its mutations and their variable transmissibility and virulence, is hard to predict using a standard SIR model. More mathematical models combined with epidemiological models can predict future pandemic potential illnesses that share similar characteristics with the SARS-CoV-2 virus. Our findings have demonstrated that the SIR model is better suited to predicting the epidemic trend caused by disease propagation since it can absorb surges and be adjusted to the recorded data. It is feasible to forecast the success of interventions by comparing reported data with predictions. The SIR model, a basic infectious disease model, was able to predict that in the presence of strategies, the infection will rise and drop quickly resulting in less mortality and morbidity, as opposed to the lack of it, resulting in more long-term damage to both the country and the healthcare. A rapid and quick application of policy changes will help in curbing the disease before it unleashes its full potential.

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Conflict of Interest: None

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