Visualizing the efficacy of vaccination in different Indian states: a comparative account with other countries

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Abstract Efficacy of the vaccination program for COVID-19 pandemic caused by SARS-CoV-2 (Severe Acute Respiratory Syndrome-CoronaVirus-2) was analyzed. The data for number of cases and vaccination, obtained from government websites from 1st January, 2020 to 10th October, 2021 for India, USA, United Kingdom, Italy, South Africa and states West Bengal, Delhi, Maharashtra, Kerala and Tamil Nadu. Modified Poisson prediction models were developed using SPSS to predict the number of cases with and without vaccination as predictor to catalogue the efficacy of vaccination. In the prediction model where vaccination was used as a predictor, the downward trend of predicted value matched with actual value, falling within the 95% confidence interval. However, individual peaks of waves were not observed clearly for the predicted values. Vaccination within the population was observed to be very critical in controlling the pandemic progression with all countries showing decrease in daily case counts as more people in the population got vaccinated. In India, owing to the huge population, more vaccination is needed for the predicted cases to fall lower.

Keywords Vaccination · SARS-CoV-2 · Negative binomial regression · Lockdown

Introduction

The corona virus disease or COVID-19 is so called, based on its causative agent, SARS-CoV-2 (Severe Acute Respiratory Syndrome Corona Virus 2), first reported during December, 2019, from Wuhan, China. The virus spread throughout the world culminating into pandemic, accentuating individuals to the ‘new normal’. Transmitted via air, apart from the respiratory tract, the virus affects other organs too causing gastrointestinal, hepatic and neurological disorders [43, 55]. While the common symptoms include fever, cough, fatigue [52, 55], severe cases culminate in pneumonia, acute respiratory distress syndrome (ARDS) [32, 43] which may subsequently conduce to death [52, 55].

As of 10th October, 2021 the worldwide tracking of COVID-19 infections reported 238,732,756 confirmed cases including 215,894,598 recovered and 4,869,929 dead [14]. The course of disease progression is different in almost all countries. Multitudinous factors explain this variability; like ethnicity, biogeography, environmental niche, co-morbidities, genetic factors, socio-economic status [2, 30, 34], social differences [33], temperature [37] and climate [45].

In the context of social differences and ethnicity, evaluation of hospitalized patients from 14 different States in USA observed 45% patients to be Caucasian, 33% African-American, 8.1% Hispanic, 5.5% Asian, less than 1% American Indian/Alaskan native and 7.9% patients belonged from unknown race(s) [30]. In the context of temperature and climate, a Brazilian study defined the association between the number of COVID-19 cases and temperature to be negative with an approximate increase in 6.4 cases per day accompanying an average 1°F fall in temperature [45]. Besides, approximately 56.01 cases were
seen to increase per day with 1 inch increase in daily precipitation [45]. These studies reiterate differences in the trend of COVID-19 spread and pattern; which besides differing among countries, also differs at various locations within a country [4].

In an effort to control the diverse trends in the pandemic transmission, stringent implementation of lockdown and social distancing was adopted as the common base by policy makers all around the world [38]. It controlled the explosion of cases causing the first wave to subside but also markedly hampered the daily lives of global population [46]. Subsequent relaxation in the government-imposed restrictions for economic purposes allowed restricted resumption of daily activities but also inflated case numbers causing subsequent waves of infection [18] and further disruption in daily life.

Social constraints due to the unremitting pandemic have adversely affected mental well-being [56]. Fear of the pandemic is tremendous among people [42]. Recurrent infectious waves increase the urgency of obtaining solutions in terms of treatment methodology, specific medication and vaccination. While specific medicine and/or uniform treatment methodology against the disease is lacking [44], many reports suggest vaccination as the only solution [51, 23, 27].

Vaccines have been developed targeting the spike protein and genome of the virus [19]. Vaccination program started from the month of December’20 or January’21 in almost all countries [36]. Visualization of the situation after vaccination is essential to assess its efficacy in bringing down the COVID-19 cases. A prediction model can help visualize fall in daily cases, subsequently marking the end for COVID-19, lockdown and social-distancing, indicating resumption of normal life.

Earlier prediction models developed for India [22], USA [57, 58] did not take into account the vaccination. Economic demands necessitate lockdown relaxation, so vaccination is the only way to overcome the pandemic. In this study, the number of people vaccinated has been focused upon to visualize how the vaccination program has affected the pandemic spread. This study aimed to compare and predict the trend of COVID-19 in different countries and Indian states in context of vaccination.

Predictions based on vaccination can not only indicate the end of the pandemic but also shed light on how well the pandemic is handled in different locations.

Details on the countries and states selected, their basis for selection and websites from where data was acquired are provided in subsequent sections. Since data was collected from publicly available information, no ethical clearance was necessary.

Countries and Indian states selected

The countries and states, most severely affected by the SARS-CoV-2 were considered in the study. USA had been the worst affected country in America [9] while Italy and UK had been worst affected in Europe [26, 10]. To encompass ethnic differences, Africa was also incorporated in the study [47, 53]. India came second when total cases were considered [5]. Among Indian states, first patient of COVID-19 was identified in Kerala [24, 1] gradually spreading to other states but the worst situation had been observed in states having high international migration-Maharashtra, Tamil Nadu, Delhi and West Bengal [41]. Hence these regions were considered for the study.

Data acquisition

Data for USA, United Kingdom, Italy, South Africa was collected from ourworldindata.org [11] while data for India, Maharashtra, Tamil Nadu, Delhi and West Bengal was collected from covid19.org [12]. The variables considered were daily count of cases and vaccination. Dataset included dates and corresponding daily new cases, cumulative confirmed cases spanning from 1st January, 2020 until 10th October, 2021 besides the total count of vaccinated people till 10th October, 2021. These parameters were recorded on a daily basis within the time span specified. As specific parameters were taken, no further normalization, screening or removal of unnecessary objects were required.

Dataset was arranged in MS Excel and all analysis was done using SPSS.

Poisson regression

Poisson regression is most commonly used to model count data. Poisson regression assumes equi-dispersion in data. If this criterion is not met, the data must be adjusted using dispersion parameter. Then, this generalized form of Poisson regression is known as negative binomial regression, which can thus be availed for prediction.
### Table 1  Deviance and Omnibus Test

| State/Country | Model Fit | Omnibus test |
|---------------|-----------|--------------|
|               | Deviance Value/df | Chi-square | Sig |
|               | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| India         | 1.272  | 1.256 | 1369.516 | 1462.206 | 0 | 0 |
| USA           | 1.241  | 1.221 | 76.591 | 240.576 | 0 | 0 |
| UK            | 1.231  | 1.215 | 244.236 | 361.609 | 0 | 0 |
| Italy         | 1.253  | 1.224 | 68.353 | 282.743 | 0 | 0 |
| South Africa  | 1.257  | 1.26 | 87.755 | 95.96 | 0 | 0 |
| West Bengal   | 1.241  | 1.215 | 79.679 | 235.816 | 0 | 0 |
| Delhi         | 1.31  | 1.242 | 19.932 | 344.264 | 0 | 0 |
| Kerala        | 1.214  | 1.192 | 463.132 | 622.617 | 0 | 0 |
| Maharashtra   | 1.192  | 1.157 | 102.517 | 304.581 | 0 | 0 |
| Tamil Nadu    | 1.231  | 1.214 | 93.788 | 194.485 | 0 | 0 |

### Table 2  Parameter Estimates for India

| Parameter       | B          | Std. Error | 95% Wald Confidence Interval |
|-----------------|------------|------------|------------------------------|
|                 | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)     | −897.596  | −1791.174 | 75.3412 | 108.0773 | −1045.262 | −2003.001 | −749.930 | −1579.346 |
| Date            | 6.569E-08 | 1.304E-07 | 5.4491E-09 | 7.8202E-09 | 5.501E-08 | 1.150E-07 | 7.637E-08 | 1.457E-07 |
| Total_vaccinations | −5.509E-09 | 4.2301E-10 | 2.240 | 1.946 | 0.1092 | 0.0975 | 2.035 | 1.764 | 2.464 | 2.146 |
| (Scale)         | 1a         | 1a         | 2.240 | 1.946 | 0.1092 | 0.0975 | 2.035 | 1.764 | 2.464 | 2.146 |

| Parameter       | Hypothesis Test |
|-----------------|-----------------|
|                 | Wald Chi-Square | df | Sig |
|                 | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)     | 141.937 | 274.667 | 1 | 1 | 0.000 | 0.000 |
| Date            | 145.321 | 277.851 | 1 | 1 | 0.000 | 0.000 |
| Total_vaccinations | 169.594 | 1 | 1 | 0.000 | 0.000 |
| (Scale)         | (Negative binomial) |

Dependent Variable: Daily_cases
Model: (Intercept), Date (Without vaccination)
Model: (Intercept), Date, Total_vaccinations (With vaccination)
aFixed at the displayed value
Model fit

To estimate equi-dispersion in the data, the deviance value divided by degree of freedom (df) is estimated. The deviance is “twice the difference between the maximum achievable log-likelihood and the log-likelihood of the fitted model”. [Deviance value/df] when equal to 1 is indicative of equi-dispersion and greater than 1 indicates over-dispersion. For the latter cases, the dispersion parameter can either be set to default or estimated under negative binomial log function. Preference to the model developed with either default or estimated dispersion parameter is based on whichever has lower AIC (Akaike Information Criterion) or BIC (Bayesian Information Criterion) values.

Omnibus test

It assesses whether all the predictors collectively improve the model prediction over intercept-only model (i.e., with no independent variables or predictors). A level of significance or p-value less than 0.05 indicate statistically significant model.

Initial evaluations showed over-dispersion in data, so the data was adjusted using the dispersion parameter by utilizing the “estimate value” function available in SPSS. The models where the dispersion parameter was calculated based on the data (and not default value of dispersion parameter used), showed lower AIC and BIC values. This held true for all selected locations. Thus, negative binomial regression models with estimated dispersion parameter were preferred and henceforth represented.

Results

For each selected location, two negative binomial regression models were developed- one with vaccination as the predictor, the other without vaccination as a predictor so as to catalogue the effectiveness of vaccination in altering the trend of the pandemic.
Table 4 Parameter Estimates for UK

| Parameter            | B Without vaccination | Std. Error Without vaccination | 95% Wald Confidence Interval Without vaccination | B With vaccination | Std. Error With vaccination | 95% Wald Confidence Interval With vaccination |
|----------------------|-----------------------|--------------------------------|-------------------------------------------------|-------------------|-----------------------------|-----------------------------------------------|
| (Intercept)          | -943.659              | -1673.364                      | -1055.622                                       | -1832.808         | -831.695                    | -1513.920                                     |
| Date                 | 6.891E-08             | 1.217E-07                      | 0.0789                                          | 1.102E-07         | 7.701E-08                   | 1.333E-07                                     |
| Total_vaccinations   | -2.676E-08            | 2.4976E-09                     | -3.166E-08                                      | -5.704E-08        | -2.187E-08                  | -4.374E-08                                    |
| (Scale)              | 1\(^a\)              | 1\(^a\)                        |                                                 |                   |                             |                                               |
| (Negative binomial)  | 1.597                 | 1.366                           | 0.0692                                          | 1.450             | 1.237                       | 1.759                                         |

Parameter Hypothesis Test

| Wald Chi-Square Without vaccination | Wald Chi-Square With vaccination | df | Sig | Wald Chi-Square Without vaccination | Wald Chi-Square With vaccination | df | Sig |
|------------------------------------|---------------------------------|----|-----|------------------------------------|---------------------------------|----|-----|
| (Intercept)                        | 272.881                         | 1  | 0.000 | 0.000                              | 0.000                           |    |     |
| Date                               | 278.180                         | 1  | 0.000 | 0.000                              | 0.000                           |    |     |
| Total_vaccinations                 | 114.810                         | 1  | 0.000 | 0.000                              | 0.000                           |    |     |

\(\text{aFixed at the displayed value}\)

**Prediction of daily cases in different countries and states**

Dispersion, AIC and BIC value for each individual prediction model for each location has been tabulated (Table 1). All the generated prediction models were found to be statistically significant (\(p < 0.05\)) as indicated by Omnibus test (Table 1).

The models coefficients have been tabulated in Tables 2, 3, 4, 5, 6, 7, 8, 9, 10, 11. All the predictors were significant for every model (\(p < 0.05\)); this reinforces the Omnibus test results (Tables 2, 3, 4, 5, 6, 7, 8, 9, 10, 11).

**Daily cases versus predicted value of mean of response by date for countries**

India (Fig. 1a) saw the peak of first wave in August–September 2020 which was followed by a gradual decline in counts reaching a minimum in February–March 2021. However, a more severe second wave peaked in May, 2021 (Fig. 1a). In the model without vaccination, the predicted cases show no inclination to decrease from the upward trend (Fig. 1a.1) but when vaccination is used as a predictor, although the predicted model did not conform to the initial dip after the first wave, the best fitting predicted curve did conform to the current downward trend (Fig. 1a.2).

United States’ data analysis showed the first wave peaking in April’20, a second wave in July’20, a more severe third wave in January’21 and since the onset of vaccination, a smaller fourth wave in April’21 (Fig. 1b). Same as in the previous case, the predictive model without vaccination as an independent variable, the upward rising cases did not decrease (Fig. 1b.1). As per the model generated with vaccination, the predicted curve for USA is initially seen to reach towards x-axis indicating control in COVID-19 cases (Fig. 1b.2) but in conformation to the ongoing infection wave, it turned upwards again. Similar observations were found for United Kingdom (Fig. 1c); the surge in number of predicted cases corresponding to the current infection wave (Fig. 1c.2) exceeds that of the previous peaks, which was not observed for USA.
In case of Italy (Fig. 1d), the first wave arrived at its peak during March’20. However, due to relaxation of lockdown a more severe second wave set in and peaked in November’20. A third wave peaked in March’21, though it was relatively smaller, probably due to the onset of vaccination. As in the previous cases, the model without vaccination as a predictor did not show decrease in case counts (Fig. 1d.1). But for the model involving vaccination, although the predicted peak did not correspond the actual case peak, followed a downward trend from the month of March’21 (Fig. 1d.2).

Similar observations were recorded for South Africa (Fig. 1e) although the infections peaked at a later time compared to Italy.

### Table 5 Parameter Estimates for Italy

| Parameter             | Std. Error | 95% Wald Confidence Interval | Lower | Upper     |
|-----------------------|------------|-----------------------------|-------|-----------|
|                       | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)           | -1346.843  | 71.124                      | 68.4198 | -1480.943 | -473.222             | -1212.743       |
| Date                  | 9.808E-08  | 5.1442E-09                  | 4.9511E-09 | 3.486E-08  | 8.838E-08             | 5.503E-08       |
| Total_vaccinations    | -4.418E-08 | 2.6128E-09                  | 1.685  | 1.290     | 2.040                 | 1.572           |
| (Scale)               | 1a         | 1a                          |        |           |                      |                 |

### Table 5 Parameter Estimates for Italy (Continued)

| Parameter             | Wald Chi-Square | df | Sig |
|-----------------------|-----------------|----|-----|
|                       | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)           | 74.191          | 1  | 0.000       |
| Date                  | 76.342          | 1  | 0.000       |
| Total_vaccinations    | 285.904         | 1  | 0.000       |

Dependent Variable: Daily_cases
Model: (Intercept), Date (Without vaccination)
Model: (Intercept), Date, Total_vaccinations (With vaccination)

In case of India, the first wave arrived at its peak during March’20. However, due to relaxation of lockdown a more severe second wave set in and peaked in November’20. A third wave peaked in March’21, though it was relatively smaller, probably due to the onset of vaccination. As in the previous cases, the model without vaccination as a predictor did not show decrease in case counts (Fig. 1d.1). But for the model involving vaccination, although the predicted peak did not correspond the actual case peak, followed a downward trend from the month of March’21 (Fig. 1d.2). Similar observations were recorded for South Africa (Fig. 1e) although the infections peaked at a later time compared to Italy.

### Daily cases versus value of predicted value of mean of response by date for Indian states

West Bengal (Fig. 2a) witnessed the first wave to peak in November’20, followed by a gradual decline, reaching minimum in February–March’21. However, a more severe second wave commenced, peaking during May’21 conforming to the Indian scenario as a whole. While the predicted curve without vaccination showed no decline (Fig. 2a.1), as opposed to the predicted curve with vaccination (Fig. 2a.2) indicating vaccination to be effective in controlling the pandemic spread.

In case of Delhi (Fig. 2b), the first wave of infection had three peaks- in the month of June’20, September’20 and November’20. A more severe second wave was observed between February’21 and April’21. Both the predicted curves- with vaccination (Fig. 2b.1) and without vaccination (Fig. 2b.2) differ from each other, when vaccination is included as a predictor, the predicted daily cases fall conforming to the actual scenario.

Kerala data analysis showed (Fig. 2c) the first wave to peak in October’20 and a more severe second wave peaking in May’21. Without vaccination, the predicted cases don’t show any decrease (Fig. 2c.1) but with vaccination as a predictor, the model predicts decline in cases (Fig. 2c.2).

Maharashtra saw (Fig. 2d) the first wave reaching its peak in September’20 and a more severe second wave
peaking in May’21. Vaccination as a predictor (Fig. 2d.2) altered the predicted curve without vaccination (Fig. 2d.1) to a great extent. The downward trend obtained signified the efficacy of vaccination in Maharashtra.

Tamil Nadu (Fig. 2e) saw the first wave from April 2020 to January2021. The more severe second wave peaked in June’21. Similar to the observations in case of West Bengal, Delhi, Kerala and Maharashtra, both the predicted curves with and without vaccination as a predictor (Fig. 2e.2 and e.1, respectively) differed from each other, with the prior showing inclination towards the x-axis.

The estimated curves with vaccination shows higher requirements of vaccination for all States (excluding Delhi) for controlling the pandemic.

For the models where vaccination is used as a predictor, the actual number of cases falls within the 95% confidence interval (CI) during the latter part simultaneous to ongoing vaccination program for maximum countries (Fig. 3) and Indian States (Fig. 4).

Proportion of people vaccinated in the selected countries and Indian States has been graphically represented in Fig. 5. Highest proportion of the population has been vaccinated in United Kingdom while the lowest proportion to receive at least one dose of vaccine was seen in South Africa. Among the Indian States, the highest proportion of people to receive at least one dose of vaccine by 10th October, 2021 was Kerala while the lowest numbers were recorded in West Bengal.

**Discussion**

India, USA, Italy, UK, South Africa and within India, Maharashtra, Delhi, Tamil Nadu, Kerala, West Bengal constitute populations belonging to varying ethnicity, biogeography and climate. This justified generation of individual prediction model for each location. The estimated models portrayed that the trend of rising cases change once vaccination was implemented.

Vaccination engendered decrease in daily cases for India mid-May, 2021 onwards before which the Indian scenario was very severe with continual inflation in case counts. The
first and second waves happened within the space of five months. Effectiveness of social distancing, mask usage and lockdown most probably controlled the first wave. Most importantly, ending of first wave at mid-week of February was likely a result of experience gained from the initial months by the medical experts in treating COVID-19.

However, case counts surged on 15 April, 2021 with number of daily cases being 0.2 million. Speculative reasons for the surge firstly include the double mutant variants of SARS-CoV-2 (B.1.617 lineage) identified in Maharashtra, West Bengal and Delhi in April, 2021 [21], which were reportedly more infectious than the first wild type variants of early 2020 [6]. Besides, UK and South African variants detected in Kerala in April’21 [50] were reportedly more transmissible than the original [40], thus bolstering case counts.

Secondly, mass gathering in Kumbhmela [31], festivals like Bihu [13], national farmers’ movement [28] and election [28] in several states spawned negligent behavior in the population. Thirdly, natural disasters like cyclone ‘Yaas’ in West Bengal [16], ‘Taufkae’ in Delhi, Maharashtra, Kerala and Tamil Nadu [17] that hit the states amid a devastating second wave of COVID-19 led to worsening in handling the spread of virus.

The second wave was again met with lockdown although dates and restriction varied across different states. Delhi went under lockdown from 19th April 2021 [3]. Maharashtra imposed weekend lockdown from 4th April, 2021[35]. Lockdown in Tamil Nadu began from 10th May, 2021 [8]. West Bengal imposed complete lockdown from 16th May, 2021 [54]. Kerala saw strict lockdown from 8th May, 2021 to handle the second wave [29].

Vaccination in India started from 16th January, 2021. By 10th October, 2021, Number of vaccine doses to the population ratio in West Bengal was 0.64, in Delhi 1.01, in Kerala 1.02, in Maharashtra 0.71 and in Tamil Nadu 0.66 (Fig. 5). Starting from January’21 mid-week till 10th October’21, 68.9% of the total Indian population got at least first dose of vaccine. Number of vaccine doses to the population ratio was 0.68. The effectiveness of vaccination combined with lockdown measures imposed in various
individual states can be viewed in the downward trend of daily cases in the prediction model (Fig. 2).

Compared to India, the United States of America faced a more severe form of pandemic. The government-imposed measures such as lockdown, social distancing, and wearing a mask controlled the first wave while subsequent relaxation pushed the nation into second stage with semi-free transmission. Amid the pandemic, last week of May’20, saw a country-wide movement due to racial discrimination issues, with participation of 140 cities in 22 states of USA [58] which might have bolstered the daily confirmed case counts leading to the third wave in USA. Vaccination started from the mid-week of December, 2020. Number of vaccine doses to the population ratio was 1.21 in USA (till 10th October, 2021) (Fig. 5) indicating complete vaccination of many within the population.

Although USA was worst hit by the pandemic, deaths per million recorded in the United Kingdom were very high. SARS-CoV-2 double mutated variants, 40–80% more transmissible than wild type variant [20] first identified in UK in November’20 [15, 39, 49] might have been responsible for the second wave. Accumulation of mutations however could not be incorporated within the prediction model, which has perhaps caused the best fitting predictive curve to not completely conform to the actual daily case counts, despite being significant (Fig. 1). Vaccination started from the mid-week of December, 2020 in UK. Number of vaccine doses to the population ratio was 1.39 by 10th October, 2021 (Fig. 5).

Besides UK, Italy also faced a severe form of the pandemic. Stringent lockdown measures were eased after the first wave. In September’20, school reopening was considered “an absolute priority” [25]. Reinstatement of daily activities, crowding in public transport [7] impaired social distancing causing the next surge in October’20. Vaccination program started from the last week of December in Italy. Number of vaccine doses to the population ratio was 1.42 by 10th October, 2021 (Fig. 5). On inclusion of vaccination as a predictor for model development, daily case counts in predictive model were observed to decrease (Fig. 1d). With the predictive curve dropping towards the

| Parameter Estimates for Delhi | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
|------------------------------|--------------------|-----------------|--------------------|-----------------|--------------------|-----------------|--------------------|-----------------|
| (Intercept)                  | -391.532           | -1652.708       | 87.7473            | 89.2619         | -563.513           | -1827.658       | -219.550           | -1477.758       |
| Date                         | 2.888E-08          | 1.201E-07       | 6.3457E-09         | 6.4582E-09      | 1.644E-08          | 1.075E-07       | 4.131E-08          | 1.328E-07       |
| Total_vaccinations           | -4.923E-07         | 1.7431E-08      | 2.921              | 1.545           | -5.265E-07         | -4.581E-07      | 2.764              | 1.879           |
| (Scale)                      | 1^a                | 1^a             | 0.1205             | 0.0852          | 2.291              | 1.545           | 2.764              | 1.879           |
| (Negative binomial)          | 2.516              | 1.704           | 0.1205             | 0.0852          | 2.291              | 1.545           | 2.764              | 1.879           |

Table 8 Parameter Estimates for Delhi

| Parameter | Hypothesis Test | Wald Chi-Square | df | Sig |
|-----------|-----------------|-----------------|----|-----|
| (Intercept) |                  | 19.910          | 1  | 0.000 |
| Date       |                  | 20.707          | 1  | 0.000 |
| Total_vaccinations |            | 797.694         | 1  | 0.000 |

Dependent Variable: Daily_cases
Model: (Intercept), Date (Without vaccination)
Model: (Intercept), Date, Total_vaccinations (With vaccination)

^a Fixed at the displayed value
x-axis, vaccination can be held as the primary accountable factor in controlling the pandemic.

Compared to other locations, South Africa faced a less severe form of the pandemic. Strict lockdown policy controlled first wave following which lockdown was relaxed to overcome economic crisis during pandemic [48]. Double mutant strains of SARS-CoV-2 (B.1.351) reported in the month of December’20, were assessed to be more transmissible [6]. On 17th February’21, South Africa started vaccination program. Number of vaccine doses to the population ratio was 0.31 by 10th October, 2021 (Fig. 5).

Vaccination might have been the key factor in controlling the third wave here.

As vaccination progress, the actual cases decrease, fall within the upper and lower bounds of 95% CI and models become more efficient. Although the estimated daily case counts started showing a downward trend, in some cases, it rose again. Further vaccination, meting double doses to entire population, can effectuate an end to the current situation.

| Table 9 | Parameter Estimates for Kerala |
|---------|------------------|------------------|-------------------|-------------------|------------------|
|         | B                | Std. Error       | 95% Wald Confidence Interval |
|         | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept) | -1607.629        | -2773.066        | 68.3821           | 105.2116         | -1741.656         | -2979.277         | -1473.603         | -2566.855         |
| Date     | 1.169E-07        | 2.012E-07        | 4.9453E-09        | 7.6121E-09       | 1.072E-07         | 1.863E-07         | 1.266E-07         | 2.161E-07         |
| Total_vaccinations | -1.242E-07        | 8.7259E-09       |                   |                   |                   |                   |                   |                   |
| (Scale)  | 1*               | 1*               |                   |                   |                   |                   |                   |                   |
| (Negative binomial) | 1.419           | 1.142            | 0.0731            | 0.0606           | 1.283             | 1.030             | 1.570             | 1.268             |

| Parameter | Hypothesis Test |
|-----------|------------------|
| Wald Chi-Square | df | Sig |
| Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept) | 552.697          | 694.694          | 1                 | 1                 | 0.000             | 0.000             |
| Date       | 558.382          | 698.505          | 1                 | 1                 | 0.000             | 0.000             |
| Total_vaccinations | 202.543          | 1                 |                   |                   | 0.000             |                   |
| (Scale)    | (Negative binomial) |       |                   |                   |                   |                   |

Dependent Variable: Daily_cases
Model: (Intercept), Date (Without vaccination)
Model: (Intercept), Date, Total_vaccinations (With vaccination)
*Fixed at the displayed value
Daily counts of confirmed cases can be successfully predicted based on the prediction models developed in the study. The prediction models were significant and predicted the best fitting confirmed case numbers based on original case counts and vaccination. All the possible causes inflating case counts could not be numerically enunciated which is a major limitation of the study. This might be the reason why the predicted numbers, although significant within 95% CI, did not completely conform to the original numbers. However, the effect of vaccination can be distinctly visualized in the predicted curves. Vaccination program is effective in controlling COVID-19 pandemic.

**Table 10** Parameter Estimates for Maharashtra

| Parameter       | B       | Std. Error | 95% Wald Confidence Interval |
|-----------------|---------|------------|-------------------------------|
|                 | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)     | -603.620 | -1417.994 57.6821 | 72.3131 | -716.675 | -1559.725 | -490.565 | -1276.263 |
| Date            | 4.432E-08 | 1.033E-07 4.1713E-09 | 5.2319E-09 | 3.614E-08 | 9.300E-08 | 5.249E-08 | 1.135E-07 |
| Total_vaccinations | -5.628E-08 | 3.1894E-09 3.1894E-09 | 3.1894E-09 | -6.253E-08 | -5.003E-08 |
| (Scale)         | 1^a     | 1^a        | 0.0635 | 0.0500    | 1.132    | 0.864    | 1.381    |
| (Negative binomial) | 1.250        | 0.957 0.0635 | 0.0500    | 1.132    | 0.864    | 1.381    |

| Parameter       | Wald Chi-Square | df | Sig |
|-----------------|-----------------|----|-----|
|                 | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)     | 109.508          | 384.517 | 1   | 1   | 0.000    | 0.000 |
| Date            | 112.879          | 389.464 | 1   | 1   | 0.000    | 0.000 |
| Total_vaccinations | 311.381    | 1   | 0.000 |
| (Scale)         | (Negative binomial) |

Dependent Variable: Daily_cases
Model: (Intercept), Date (Without vaccination)
Model: (Intercept), Date, Total_vaccinations (With vaccination)
^aFixed at the displayed value
Table 11 Parameter Estimates for Tamil Nadu

| Parameter      | B               | Std. Error | 95% Wald Confidence Interval | Wald Chi-Square | df | Sig     |
|----------------|-----------------|------------|-------------------------------|----------------|----|---------|
|                | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)    | -582.233        | -1130.920  | 58.5135                       | 76.2657        | -696.917           | -1280.398        | -467.549           | -981.442          |
| Date           | 4.271E-08       | 8.241E-08  | 4.2315E-09                    | 5.5176E-09     | 3.441E-08          | 7.160E-08        | 5.100E-08          | 9.323E-08          |
| Total_vaccinations | -7.715E-08   | 6.2703E-09 | -8.944E-08                   | -6.486E-08     |                    |                   |                    |                   |
| (Scale)        | 1^              | 1^         |                               |                |                   |                   |                    |                   |
| (Negative binomial) | 1.574       | 1.382      | 0.0795                        | 0.0709         | 1.426              | 1.250             | 1.738              | 1.528             |

Parameter Hypothesis Test

| Wald Chi-Square | df | Sig     |
|----------------|----|---------|
| Without vaccination | With vaccination | Without vaccination | With vaccination | Without vaccination | With vaccination |
| (Intercept)    | 99.011       | 219.890  | 1                        | 1              | 0.000              | 0.000           |
| Date           | 101.853      | 223.092  | 1                        | 1              | 0.000              | 0.000           |
| Total_vaccinations | 151.383     | 1        | 1                        | 0.000          |

^Fixed at the displayed value

Dependent Variable: Daily_cases

Model: (Intercept), Date (Without vaccination)
Model: (Intercept), Date, Total_vaccinations (With vaccination)
Fig. 1 Daily cases, Value of predicted value of Mean of Response by Date for countries. 

- **a.1** Daily cases, Value of predicted value of Mean of Response by Date for India (Blue line- Actual cases, Red line-Predicted value) (Without vaccination).
- **a.2** Daily cases, Value of predicted value of Mean of Response by Date for India (Blue line- Actual cases, Red line-Predicted value) (With vaccination).
- **b.1** Daily cases, Value of predicted value of Mean of Response by Date for USA (Blue line-Actual cases, Red line- Predicted value) (Without vaccination).
- **b.2** Daily cases, Value of predicted value of Mean of Response by Date for USA (Blue line-Actual cases, Red line- Predicted value) (With vaccination).
- **c.1** Daily cases, Value of predicted value of Mean of Response by Date for UK (Blue line-Actual cases, Red line- Predicted value) (Without vaccination).
- **c.2** Daily cases, Value of predicted value of Mean of Response by Date for UK (Blue line-Actual cases, Red line- Predicted value) (With vaccination).
- **d.1** Daily cases, Value of predicted value of Mean of Response by Date for Italy (Blue line-Actual cases, Red line-Predicted value) (Without vaccination).
- **d.2** Daily cases, Value of predicted value of Mean of Response by Date for Italy (Blue line-Actual cases, Red line-Predicted value) (With vaccination).
- **e.1** Daily cases, Value of predicted value of Mean of Response by Date for South Africa (Blue line-Actual cases, Red line-Predicted value) (Without vaccination).
- **e.2** Daily cases, Value of predicted value of Mean of Response by Date for South Africa (Blue line-Actual cases, Red line-Predicted value) (With vaccination).
Fig. 2 Daily cases, Value of predicted value of Mean of Response by Date for Indian states. a.1 Daily cases, Value of predicted value of Mean of Response by Date for W. Bengal (Blue line-Actual cases, Red line-Predicted value) (Without vaccination). a.2 Daily cases, Value of predicted value of Mean of Response by Date for W. Bengal (Blue line-Actual cases, Red line-Predicted value) (With vaccination). b.1 Daily cases, Value of predicted value of Mean of Response by Date for Delhi (Blue line-Actual cases, Red line-Predicted value) (Without vaccination). b.2 Daily cases, Value of predicted value of Mean of Response by Date for Delhi (Blue line-Actual cases, Red line-Predicted value) (With vaccination). c.1 Daily cases, Value of predicted value of Mean of Response by Date for Kerala (Blue line-Actual cases, Red line-Predicted value) (Without vaccination). c.2 Daily cases, Value of predicted value of Mean of Response by Date for Kerala (Blue line-Actual cases, Red line-Predicted value) (With vaccination). d.1 Daily cases, Value of predicted value of Mean of Response by Date for Maharashtra (Blue line-Actual cases, Red line-Predicted value) (Without vaccination). d.2 Daily cases, Value of predicted value of Mean of Response by Date for Maharashtra (Blue line-Actual cases, Red line-Predicted value) (With vaccination). e.1 Daily cases, Value of predicted value of Mean of Response by Date for Tamil Nadu (Blue line-Actual cases, Red line-Predicted value) (Without vaccination). e.2 Daily cases, Value of predicted value of Mean of Response by Date for Tamil Nadu (Blue line-Actual cases, Red line-Predicted value) (With vaccination).
Fig. 3  Actual cases with Lower and upper bound of confidence interval for countries (With vaccination) (green line-upper bound, red line-value for actual cases, blue line upper bound) (3a-India, 3b-USA, 3c-UK, 3d-Italy, 3e-South Africa)
Fig. 4 Actual cases with Lower and upper bound of confidence interval for Indian states (With vaccination) (green line- upper bound, red line-value for actual cases, blue line upper bound)(4a-West Bengal, 4b-Delhi, 4c-Kerala, 4d-Maharashtra, 4e-Tamil Nadu)

Fig. 5 Number of vaccine doses to the population ratio for countries and States

Vaccination in the population
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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval As this study was based on publicly available data on government websites, no ethical approval was required.

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