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A multi-stage SEIR model to predict the potential of a new COVID-19 wave in KSA after lifting all travel restrictions

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Abstract The complete lifting of travel restrictions to KSA takes place after 3rd of January 2021. There are fears that KSA will confront a new COVID-19 wave, especially when the most of countries that resumed the international flights are suffering now from the second surge. Fortunately, more than one Covid-19 Vaccine have been rolled out. However, herd immunity could be reached only through widespread vaccination. COVID-19 vaccines need more time to be properly protective, especially in front of people refusing to get vaccinated. A modified multi-stage SEIR model, with distinct reproductive numbers corresponding to before and after lockdown is employed to predict the potential of a new pandemic wave. First, the two-stage model employed to find the best fitting for the reproductive numbers. Then, the model is extended to three-stage one to investigate the relaxation. However, the modified model detects a second wave in early stage from 28th May to 17th June 2020 before even succeeding controlling the first outbreak. Subsequently, the four-stage SEIR model is used to predict the end of the second wave. Moreover, the model is employed to test the potential of a new pandemic surge after the international flights are resumed.

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1. Introduction

Based on WHO statistics, since its detection until December 25, 2020, the total number of confirmed cases worldwide is 80,133,093 and the number of deaths is 1,755,653. The considerable and continuous rise in the daily infected cases number all over the world is worrying, and many researchers are cur-
rently developing various mathematical and machine learning models to predict the future progress of this pandemic [1–7]. However, only few studies have discussed the possibility of the second surge of this SARS pandemic. Unfortunately, many countries are facing a new resurgence in COVID-19 cases after successfully slowing outbreaks early at the beginning [8–10], especially, after reopening their economies and Schools. France, UK, Italy, Spain, Greece, Czechia, Bosnia, Croatia, Slovakia, Belgium, Serbia, Slovenia and the Netherlands already are confronting the second wave.

At the beginning of the Covid-19 appearance and when no vaccine has been discovered yet and due to the absence of effective treatment, most countries resorted to complete lockdowns to confront COVID-19 rapid spread. Moreover, closing social and professional interactions helped control the outbreak of the Coronavirus, but unfortunately at a high economic and human cost.

During the first surge, not only lockdowns have been implemented but also other strict measures such as curfews have been imposed to guarantee social distancing [11,12]. However, to continue imposing these policies it seems to be impossible now due to economic reasons [13]. Nevertheless, recent modeling studies have indicated that the relaxation of restrictions could have terrible penalties [4,14–16].

The second wave of the pandemic presents a looming threat to society, with massive loss of human lives and a destructive economic impact. A century ago, the Spanish flu that devastated population where the second wave of the pandemic killed substantially more people than the first one. Consequently, well preparing to confront the second wave should be the main objective of all countries. For instance, one of the first countries that announced that it has officially entered a second wave of infections is South Korea, but due its successful testing and tracing systems it succeeded to control the situation. Moreover, after declaring eliminated the Covid-19 first wave, New Zealand and China have both seen small new outbreaks. Many countries are living almost total isolation from the rest of the world by introducing strict travel bans. However, Europe now is facing second pandemic wave which is worse than the first one. Since most European countries are now announcing more daily cases than they were during the first outbreak. Regarding KSA, since the first COVID-19 confirmed case, which was reported on March 2, 2020, KSA has enforced strict policies to confront the pandemic spread. The summary of all measures taken by Saudi authority to tackle with the pandemic COVID-19 and hence limiting its effects is depicted in Fig. 1.

Despite all these efforts, starting with proactive decisions and imposing strict precautionary measures, as of the time of writing this article (November 14, 2020), 352,950 total cases have been reported in KSA with 5641 deaths. This reflects the high contagiousness and the rapid spread of this pandemic. Despite of the daily infected cases which are still around of 400 cases, KSA starts easing coronavirus lockdown restrictions. Moreover, the ease of the travel restrictions has started since September. But these measures will be completely lifted after 3rd January 2021. In the Middle East, KSA is counted as the second biggest tourist destination with over 15 million yearly visitors since 2012. Therefore, the risk of arriving new infectious cases is very high. Hence, there are fears that KSA will face a second COVID-19 wave, especially when the most of countries that resumed the international flights are suffering now from the second surge. The aim of this paper is to simulate the possible second wave outbreak in KSA. One of the efficient tools to study infectious disease spread is mathematical modelling. The disease dynamics is commonly modelled by compartments or complex network diffusion techniques. These models have proven their success in providing accurate time evolution of infected cases [17–24]. One of the best deterministic models employed to control infectious diseases diffusion

![Fig. 1 KSA containment policies to control the spread of COVID-19.](image-url)
and their compartmental transmission, is the Susceptible-Exposed-Infectious-Removed (SEIR) model [25–27].

Fortunately, more than one Covid-19 Vaccine have been rolled out. However, herd immunity could be reached only through widespread vaccination. COVID-19 vaccines need more time to be properly protective, especially in front of people refusing to get vaccinated. Furthermore, there is also concern about the possibility of a second wave in a lot of countries. This paper explores these issues in the context of the kingdom of Saudi Arabia by applying a modified SEIR epidemiological model. First, the model will be fitted to KSA data. Then, the model will be extended to four stages to predict and to evaluate the potential of a new pandemic wave when the international flights will be resumed, and all travel restrictions will be lifted.

2. Materials and methods

Based on the well-known SEIR model, our model represents a two-stage and three-stage SEIR models that can effectively simulate both lockdowns and relaxations. The first and second stage models are applied respectively to the period before and after the lockdown. However, the third stage is employed to model the subsequent period to the lockdown’s relaxation and to simulate the second wave possibility in KSA.

2.1. SEIR model

A deterministic SEIR model based on epidemiological status of the individuals was employed. The mathematical model is based on four compartments; the Susceptible, Exposed, Infectious and Removed (SEIR) model, as illustrated in Fig. 2.

The governing differential equations depicting the SEIR model are:

\[
\begin{align*}
\frac{dS}{dt} &= \Lambda - \mu S - \beta(t) \frac{S}{N} I \\
\frac{dE}{dt} &= \beta(t) \frac{S}{N} - (\mu + \epsilon) E \\
\frac{dI}{dt} &= \epsilon E - (\gamma + \mu + \alpha) I \\
\frac{dR}{dt} &= \gamma I - \mu R
\end{align*}
\]

where

\[
S(t) + E(t) + I(t) + R(t) = \text{constant} = N \quad \text{(the total population).}
\]

\(\Lambda\) and \(\mu\) are respectively Per-capita birth rate and natural death rate and \(\alpha\) is the average fatality rate.

\(\beta\): The transmission rate having the following values before and after the lockdown.

\[
\beta(t) = \begin{cases} 
\beta_{BL}^0 & \text{Before Lockdown : } t < t_{Lockdown} \\
\beta_{AL}^0 & \text{After Lockdown : } t \geq t_{Lockdown}
\end{cases}
\]

\(c\): The transition rate at which those in the exposed group become infectious (the reciprocal is the latent period \(t_l = \frac{1}{c}\)).

\(\gamma\): The rate of transition from infectious to removed groups in other words is the recovery rate (the reciprocal is the infectious period \(t_i = \frac{1}{\gamma}\)).

The number of deaths per unit of time \((D(t) = \frac{N}{C_0} \frac{d}{dt} N(t))\) is giving by:

\[
D(t) = -\frac{\dot{N}(t)}{C_0} = - (S + E + I + R)(t)
\]

2.2. Reproduction number

The reproduction \(R_0\) gives the average number of generated infection cases by an infectious individual. Therefore, it is one of the most important parameters reflecting the growth of the disease spread. It can be obtained by the ratio of the number of new infections at time step \(t\), to the corresponding total of infected individuals [28]. For the SEIR model, it is assumed

\[
R_0 = \frac{\beta(t)\epsilon}{(\epsilon + \mu)(\gamma + \alpha + \mu)}
\]

Just as for the transmission rate, \(R_0\) with different values are employed corresponding to before and after the lockdown. Denoted by \(R_{BL}^0\), the value before the lockdown, and \(R_{AL}^0\) the value afterwards, corresponding to \(\beta_{BL}^0\) and \(\beta_{AL}^0\) respectively. The two-stage SEIR model is used to identify the values of \(R_{BL}^0\) and \(R_{AL}^0\) after fitting the model to the data. This approach is accomplished by the integration of differential equations using the fourth order Runge–Kutta method. The identification of parameters fitting the data best is ensured by minimizing the sum of the squared residuals [28].

3. Numerical algorithm

The system of the differential Equations (1) is solved using a forward Euler finite-difference scheme. The time variable dis-
cretized as $t = n dt$, where $n$ is a number of time iteration and $dt$ is the time step.

$$S^{n+1} = S^n + dt \left( A - \mu S^n - \beta S^n I / N \right)$$

$$E^{n+1} = E^n + dt \left( \beta S^n I / N^a - (\mu + \epsilon) E^n \right)$$

$$F^{n+1} = F^n + dt \left[ (\beta F^n I / N^a) - (\gamma + \mu + \varepsilon) F^n \right]$$

$$R^{n+1} = R^n + dt \left[ (\gamma F^n - \mu R^n) \right]$$

$$D^n = -(S^n + E^n + F^n + R^n)(t)$$

where $D^n$ is the daily number of deaths. The system convergence is checked by evaluating $S^n + R^n + D^n = N_0$

### 4. Data description

The data used in this study are basically the daily and cumulative number of infected cases in Saudi Arabia from March 2nd, 2020 to September 21st, 2020. All collected data are published in the official website of Saudi Ministry of Health.

Most parameters are obtained from the data but some of them should be specified and justified (Table 1). All calculations started from the day zero corresponding to the first day on which 100 or more confirmed cases in KSA were reported. For KSA the day zero corresponds to March 24th, 2020.

The mean latent period $t_l$ is the difference between the incubation period and pre-symptomatic infection. A mean incubation period of 5.8 days and a pre-symptomatic period of infection of about 2 days are found after the analysis of relevant literature. The recovery rate is the inverse of the infectious period ($t_i$) is $\gamma = 1 / t_i$. In this study, $t_i$ is chosen 3.4 days based on estimations for the case of China [30].

In order to predict the COVID-19 second wave in KSA, the two-stage model will be slightly extended to three-stage model. Where a new reproduction number $R_{n}^{\text{Relax}}$ and the corresponding transmission rate $\beta_{n}^{\text{Relax}}$ will be introduced after a specified time of the relaxation. Since KSA still in the end of the first COVID-19 wave, it is hard to accurately define the value of $t_{\text{Relax}}$ for this reason it will be chosen arbitrary.

The three-stage SEIR model will be employed to predict the possible second surge. This model is an extension of the two-stage model where Eq. (2) is replaced with:

$$\beta(t) = \begin{cases} 
\beta_{\text{BL}} & \text{Before Lockdown : } t < t_{\text{Lockdown}} \\
\beta_{\text{AL}} & \text{After Lockdown : } t_{\text{Lockdown}} \leq t < t_{\text{Relax}} \\
\beta_{\text{Relax}} & \text{After the Relaxation : } t_{\text{Relax}} < t
\end{cases}$$

All calculations are elaborated using MATLAB software. First, the two-stage code is employed to learn $\beta_{\text{BL}}$, $\beta_{\text{AL}}$ and the $t_{\text{Lockdown}}$ by fitting the model to the data.

The predictive accuracy of the model is assessed applying time series cross-validation. The metrics used for this evaluation are the root mean squared error (RMSE) and mean absolute error (MAE).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \hat{x}_i)^2}{N}}$$

$$\text{MAE} = \frac{\sum_{i=1}^{N} |x_i - \hat{x}_i|}{N}$$

where $x$ and $\hat{x}$ represent respectively the actual and the predicted number of infected cases. $N$ denotes the total number of days.

### 5. Results and discussions

The predictions of covid-19 outbreak for the case of KSA are presented in this section, including results for conventional SEIR prediction, fitting the two-stage model to the daily number of infected cases, and the estimates after the relaxations using the three-stage and four-stage versions of the model. Simulations are based on data up to 21st September 2020.

#### 5.1. Limitation of the conventional SEIR model for KSA case

First, we used the conventional SEIR model to predict the daily confirmed cases in Saudi Arabia with the same input described in earlier parts of the paper.

It is so hard to attain highest fitting degree by employing one stage SEIR model, since KSA has implemented different successive restrictions and policies for cities to flatten the daily infected cases since the beginning of the COVID-19 outbreak previously detailed in (Fig. 1). For instance, the Saudi Authority has imposed the round-the-clock lockdowns in most cities (Riyadh, Dammam, Hofuf, Dhahran and Tabuk) on April 6th, 2020. The same measures were also imposed two days earlier on the governorates of Jeddah, Taif, Qatif and Khobar. However, the round-the-clock lockdowns was imposed in all cities from May 22nd, 2020 to May 27th, 2020. From the actual data in the Fig. 3, it is clearly noticed the decrease of infected cases about 45% (from 2840 to 1581 confirmed) during the same period of the lockdown (highlighted by the solid-line circle). Here the usefulness of the lockdown is very clear since a great reduction of confirmed cases 45% was achieved during a short period of time only 5 days. Consequently, the lockdown remains one of the best measures to face the pandemic outbreak. However, the conventional SEIR model cannot detect the decrease of the number of infected (solid-line circle in Fig. 3) during the lockdown period. Because of the sudden decrease of the reproductive number as consequence of the lockdown. Similar behavior is detected also from June 16th to June 23rd, 2020 (highlighted by the dashed-line circle in Fig. 3). Since lockdown is re-imposed in Jeddah from 6 to 20 June. Partial curfew is imposed in all regions from 6 AM to 8 PM, from May 31st and June 20th, with the exception of Mecca where round-the-clock lockdown will remain imposed. Moreover, the sudden increase of the daily infected

| Parameter | Value |
|-----------|-------|
| Mean latent period $t_l$ | 3.8 days [29] |
| Mean infectious period, $t_i$ | 3.4 days [30] |
| Fatality rate $\alpha$ | 0.66% [31] |
| Before and after lockdown reproductive numbers, $R_{n}^{\text{BL}}$ and $R_{n}^{\text{AL}}$ | Estimated from fitting model to data |
| Effective date of lockdown | Estimated from fitting model to data |
cases from June 23rd, 2020 is explained by the fact of the curfew lifting in all regions had been on June 21st, 2020. Since then, all commercial and economic activities returned in all Saudi cities and regions. Therefore, the limitation of the conventional SEIR to fit and detect the lockdown and the relaxation is clearly noticed here. To overcome this limitation the two stage SEIR model is employed first to fit the actual data and to learn the reproductive number $R_{0BL}$ and $R_{0AL}$ corresponding respectively to before and after lockdown. Then the three stage SEIR model will be used to predict the COVID-19 spread after the lockdown relaxation.

5.2. Two-stage SEIR model fitting to the data

The two-stage SEIR model was employed to ensure the best fit to the actual data starting from the day zero (March 24th) to 27th May 2020. From Fig. 4, it is noticeable that it is suitable to employ the two stage SEIR model to well represent all the time variation of the daily cases. The best fitting parameters have been obtained by using the non-linear curve-fitting function (lsqcurvefit). The pre-lockdown $R_0$ values, $R_{0BL}$, represent the situation for about one week prior to the lockdown. It seems at the beginning that the determination of $t_{lockdown}$ is simple and it is equal to the date of the lockdown implementation. However, the value of $t_{lockdown}$ is obtained by finding which day gives the best fit to the data and it is relative to the effective lockdown. This is achieved by setting $t_{lockdown}$ to a particular value, say seven days, then integrating the differential equations to find the best fitting for the parameters $E_0$, $\beta_{BL}$ and $\beta_{AL}$.

The degree of the model fitting is evaluated by the $R^2$ value (0.92). The effect of lockdown is obvious here reflected by reducing the number of daily confirmed cases just after the lockdown declaration (May 22nd, 2020). Unlike conventional SEIR, the two-stage model captures well the resulting lockdown impact. Moreover, the two-stage model empowers the time delay between infection and subsequent confirmation to be identified. This time delay is given by the difference between $t_{lockdown}$ and the actual date of the lockdown (May 22nd, 2020) found here equals to 3 days. This finding is coherent with the intensive testing policy adopted by KSA since the first reported cases. Nevertheless, it could also reflect the effect of other interventions prior to the lockdown previously detailed in Section 2.

The reproductive numbers $R_{0BL}$ and $R_{0AL}$ corresponding respectively to before and after lockdown are presented in Table 2 with $R^2$ value, RMSE and MAE. $R_{0BL}$ represent the situation for about one week before to the lockdown. The pre-lockdown $R_{0BL}$ value in Table 2 is consistent with results found in the literature [32,33]. Regarding after lockdown, we notice that the $R_{0AL}$ values is below one which proves the effectiveness of the lockdowns as measures. This is in agreement with the findings in [32] for KSA. Though, the situation has rapidly changed with more recent data as we shall see in next Section 5.3.

5.3. The three-stage SEIR model prediction after lockdown relaxation

The two-stage model was used first to identify parameters $R_{0BL}$ and $R_{0AL}$ and the value of $t_{lockdown}$ corresponding to before and after Lockdown. By the same way, the prediction is carried out until the specified time of the relaxation where $R_{0AL}$ is the pre-relaxation value of $R_0$ and a new post-relaxation value $R_{0Relax}$ is introduced.

The prediction in Fig. 5 is achieved by estimating the time at which the relaxation took effect, $t_{relax}$, and the resulting reproductive number, $R_{0Relax}$. First the two-stage model was applied to find $t_{lockdown}$ based on data up to 27th May 2020.
and then using the three-stage model to determine $t_{\text{relax}}$, $R_{BL}^0$, $R_{AL}^0$, and $R_{R\text{relax}}^0$ based on data up to 10th June.

By fitting the three-stage model to data up to 10th June 2020, $t_{\text{relax}}$ is found to be on 28th May corresponding to 87 days after day zero, and the estimated value for the reproductive number is $R_{R\text{relax}}^0 = 1.49$ (95% CI: 1.41–1.56). After the fitting, a good agreement is achieved by comparing the model predictions with recent data up to 22nd June (presented blue crosses in Fig. 5).

Broadly, the predictions emphasize the capacity of the three-stage model to examine not only lockdowns, but also relaxations, including the detection of $t_{\text{relax}}$ at which start the relaxation.

5.4. Prediction of a possible second surge after lifting international flight restrictions

Nevertheless, it is also obvious that the confirmed cases had peaked for a second time (Fig. 6). Therefore, the modified model detects a second wave in early stage from 28th May to 17th June 2020 before even succeeding controlling the first outbreak. This is in align with the restrictions having been imposed in various KSA cities and regions. By the same approach applied in the two-stage model to identify $t_{\text{lockdown}}$, it should be possible to determine the time at which these measures took effect. For this reason, the model was extended to a four-stage model. First, the two-stage model was employed to determine $t_{\text{lockdown}}$, and then the three-stage model for $t_{\text{relax}}$. Later, these values are used as input into the four-stage model to identify all parameters related to the second peak. Using data up to 21st September 2020, corresponding to 151 days after day zero, the prediction identifies a $R_{R\text{relax}}^0$ value after the second peak of 0.98 (95% CI: 0.97–1.02), which is very similar to the result previously obtained for $R_{AL}^0$ after the first peak (Table 2).

After fitting the four-stage SEIR model to the real data, it is extended to explore the potential effects of lifting international flight restrictions (Fig. 7). There are many fears of a new COVID-19 outbreak since KSA the first worldwide religious touristic destination increases the degree of susceptibility to infectious from other countries visitors. Moreover, lifting of complete restrictions on international flights from and to KSA takes place after 3rd of January 2021. Similar to lockdowns which were modelled as change in the reproductive number, the lifting of the flight restrictions will be represented by increasing the reproductive number by a percentage of the difference between the $R_0$ values corresponding to before and after lockdowns learnt from four-stage SEIR model. Moreover, the proactive measures taken during the visitor’s arrival like a 14-day quarantine period on arrival and RT-PCR test within 72 h prior to departure are modelled as relaxations. The lifting international flight restrictions is assumed to take effect by 18/01/21, which corresponds to the lifting of travel restrictions on 03/01/21. Two scenarios are considered:

(i) 25% relaxation - $R_{R\text{relax}}^0 = 0.75 \times R_{BL}^0 + 0.25 \times R_{AL}^0$
(ii) 50% relaxation - $R_{R\text{relax}}^0 = 0.5 \times R_{BL}^0 + 0.5 \times R_{AL}^0$

| $R_{BL}^0$ | $R_{AL}^0$ | $R_0^2$ | RMSE | MAE |
|------------|------------|---------|------|-----|
| 2.03 (1.81–2.25) | 0.97 (0.96–0.99) | 0.89 | 419 | 324 |

Fig. 4 Results obtained by applying the two-stage SEIR model to the daily confirmed cases for KSA up to 27th May 2020.
The percentage of relaxation is obtained by increasing the reproductive number after the travel restrictions lifting denoted by $R_0^\text{Relax}$ by summing $R_0^\text{AL}$ and $R_0^\text{BL}$ with different ratio. Hence, the higher reproductive number $R_0^\text{Relax}$ corresponds to higher percentage of $R_0^\text{BL}$ which is greater than $R_0^\text{AL}$. 25% relaxations means that the proactive measures taken during the visitor’s arrival are almost strict like by imposing 14-day quarantine and RT-PCR test. However, 50% relaxations means that not strict and soft precautionary measures are taken during the arrivals. The choice of these levels of relaxations is to have an idea about the evolution of the number of infections if strict precautionary measures are not taken or partially imposed. Results are presented in Fig. 7 for daily confirmed cases and include estimates up to 26th of May 2021. The model detects a new peak on 22/03/21 with a 1930 daily infected cases for 25% relaxations. However, for the scenario of 50% relaxations corresponding to high degree of easing of the travel measures, the peak occurs earlier on 10/03/21. The difference between a 25% and 50% relaxation is remarkable with the latter leading to a considerable increase in the number of cases (2880 daily infected cases) by the beginning of March 2021. This peak is almost equal to the number of daily confirmed cases during the first wave. Hence, we can conclude that adopting rigorous quarantine rules and if travelers should be required to undergo a RT-PCR test within 72 h prior to departure corresponding to relaxation lower than 25% can keep imported cases of the disease from sparking new locally transmitted outbreaks.
6. Conclusion

A two-stage SEIR model has been fitted first to the actual data, different reproductive numbers corresponding to before and after lockdown were learnt from estimates. The model predictive accuracy was evaluated using time series by evaluating $R^2$ value, RMSAE and MAE. According to the results, the lockdown successfully slowed the covid-19 spread resulting a reduced reproductive number from 2.03 to 0.97 during the first wave. Then, the model was extended to three-stage one to investigate the relaxation impact. However, the modified model detected a second wave in early stage from 28th May

![Graph](image-url)

**Fig. 6** Predictions after applying the four-stage model to data up to 21/09/20.

![Graph](image-url)

**Fig. 7** Prediction of a possible second surge after lifting international flight restrictions.
to 17th June 2020 before even succeeding controlling the first outbreak. Subsequently, the four-stage SEIR model was used to predict the end of the second wave. Moreover, the model was employed to test the potential of a new pandemic surge after the international flights are resumed. Results based on data up to 21st September 2020 have shown that the daily confirmed cases could peak for a third time on 10/03/21 with about 3000 daily infected cases if travel measures and rigorous quarantine rules will not be properly adopted. In conclusion, even that the situation seems to be under control in KSA, but a lot of caution is needed to avoid new transmitted outbreaks by imported cases after the complete lifting of travel restrictions.

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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