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Research article

The impact of intervention strategies and prevention measurements for controlling COVID-19 outbreak in Saudi Arabia

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Abstract: On 11 March 2020, the World Health Organization announced the novel coronavirus COVID-19 outbreak as a pandemic due to the rapid growth in the number of cases worldwide. The ability of countries to contain and mitigate interventions is crucial in controlling the exponential spread of the novel virus. Several social distancing and control measurements have been applied in Saudi Arabia to mitigate COVID-19 epidemic such as quarantine, schools closure, suspending travels, reducing crowds, people movement restrictions, self-isolation and contacts tracing. This research aims to study the country interventions in Saudi Arabia and their impact on decreasing the spread of COVID-19. This paper examined different control measurements scenarios produced by a modified SEIR mathematical model with an emphasis on testing capacity expansion and number of critical cases. The modified SEIR mathematical model is solved numerically using Rung-Kutta analysis method for solving the modified SEIR system of ordinary differential equations. The simulation results revealed that the interventions are vital to flatten the virus spread curve. Early implementation of country interventions can delay the peak and decrease the population fatality rate.

Keywords: COVID-19; control measurements; interventions; mathematical modeling; SEIR; testing; critical cases

1. Introduction

Modeling and simulation are essential decision mechanisms that are valuable to measure diseases outbreak and pandemic [1]. Nonetheless, as each disease reveals specifics spread characteristics, simulation models need to be amended for each disease epidemic to handle the new circumstances. On 11 March 2020, the World Health Organization has declared the novel coronavirus COVID-19 outbreak as a pandemic. The mitigation interventions implemented in many countries are significant and have different effects in decreasing the exponential spread of novel virus [2,3]. The standard reproductive value (R) of COVID-19 is 2.2 [4,5]. There are evidences of viral shedding from asymptomatic COVID-19 infected [6,7]. During COVID-19 outbreak, reliable estimates are key to determine required health capacities and provide information and assistance for the health authorities and decision makers. Considering COVID-19 outbreak, the estimation of the key epidemiological parameters and studying the impacts of various possible control measurements to mitigate the epidemic are crucial.

For COVID-19 containment, most countries applied several intervention approaches such as cities lock-down [8]. Some countries applied mitigation method to slow down COVID-19 but not stopping the spread of the virus [9,10]. Reducing the mortality to the lowest possible rate is considered a vital priority for governments [11,12]. Hence, countries have to apply some measures to decrease mortality rate of COVID-19 [13,14]. Many predication and analysis models of COVID-19 coronavirus epidemic in different countries have been developed [5,7,15–21]. In the studies [15,19] inflection point and possible ending time in China were estimated. The study of [22] claimed that short-term country based intervention started in early stage of COVID-19 spread can only delay the peak number of infected cases. A research to analyze the effect of Germany government intervention is discussed in [23]. The study found out that the Germany government intervention has mitigated the spreading rate of COVID-19. The study in [24] claimed that country moderate lockdown decreases COVID-19 spreading rate by 25%, while country hard lockdown COVID-19 spreading rate reductions is 44%. The model assumes that population age and climate have no effect on COVID-19 spreading rate.

Saudi Arabia has solid readiness and health capabilities supported by the experience achieved throughout the managing and controlling MERS-CoV outbreak in 2014 [25,26]. Furthermore, Saudi Arabia has gained experience of handling public heath emergencies during organizing and managing of the Hajj in the time of international diseases epidemics such as H1N1, ZIKA, SARS and MERS [26–28]. Saudi Arabia authorities implemented several intervention strategies and control measurements to contain COVID-19 outbreak such as quarantine, social distance, schools closure, suspending travels, reducing crowds, people movement restrictions, self-isolation, contact tracing. Figure 1 describes the interventions and control measurements implemented by Saudi authorities to mitigate the spread of COVID-19.

To avoid overwhelming of health care systems, the Kingdom of Saudi Arabia ministry of health considered two factors, monitoring critical cases numbers and expanding testing capacity. Testing more cases is a crucial factor of understanding the scale of the epidemic and how it is growing. The main reason for expanding testing capacity is to find cases, isolate them, slow down the transmission and decrease the number of cases. Yet, it is unknown to what extend these interventions and control measurements have had an effect in containing COVID-19 outbreak.

Based on the epidemiological feature of COVID-19 and the country based intervention applied by Saudi authorities, this study extended the classical ‘Susceptible-Exposed-Infected-Removed’ (SEIR) to illustrate the transmission of COVID-19 in Saudi Arabia. The modified conceptual framework has an extra classes “I_c” represents critical cases and tested infected “I_t”.

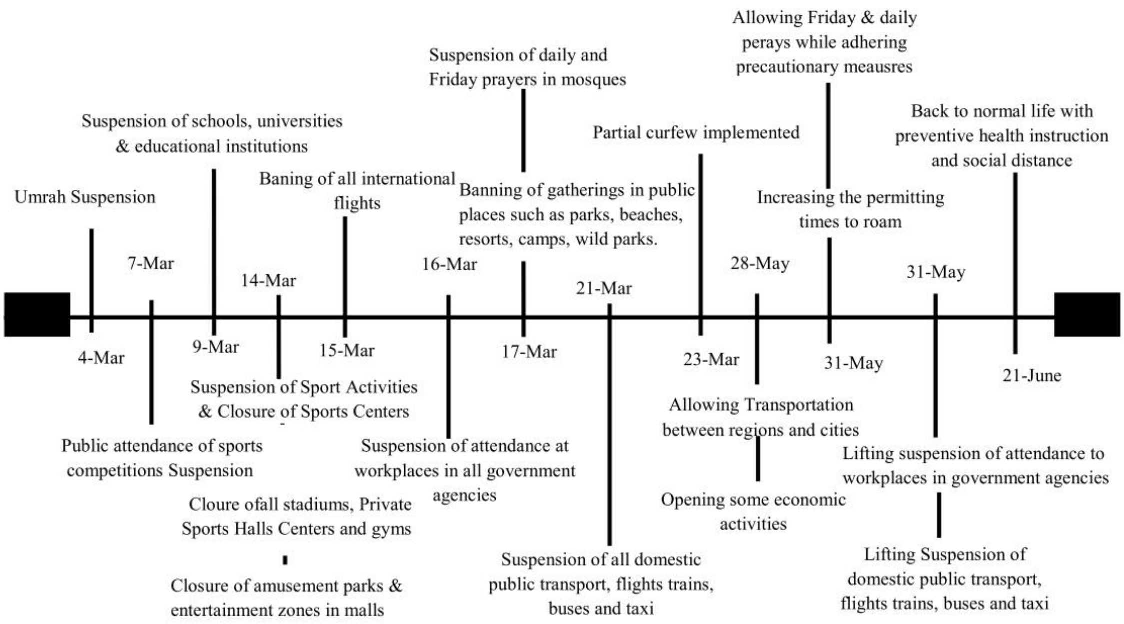

Figure 1. Control measurements and interventions implemented in Kingdom of Saudi Arabia [26].

This paper contains four sections. Section two describes the methods and materials. The experimentations and results are analyzed in section three. We concluded in section four.

2. Methods and materials

2.1. Data source

The modified SEIR mathematical model is solved numerically, using the Matlab software with ode45 tool for solving ordinary differential equations. The ode45 differential equations solver incorporate Rung-Kutta numerical analysis mechanism for solving the proposed system of ordinary differential equation. The standard formula of ode45 is described in Eq (2.1)

$$[\mathrm{t},\mathrm{y}] = \mathrm{ode45}(\mathrm{odefun},\mathrm{tspan},\mathrm{y}_0), \tag{2.1}$$

where $\mathrm{tspan} = [\mathrm{t}_0\ t_f]$. The ode45 integrates the system of differential equations $\mathrm{y}' = \mathrm{f}(\mathrm{t},\mathrm{y})$ from t_0 to t_f and y_0 is the initial conditions. The ode45 solution is a matrix in which each row y represents a value in column vector t.

In the modified SIER model, Runge–Kutta numerical analysis methods are applied in time-based approximations solutions of the proposed system of differential equations. Runge–Kutta are a set of implicit and explicit iterative approaches based on Euler methods.

The Saudi Ministry of Health reports COVID-19 data daily in online dashboard [29]. More data were obtained from Johns Hopkins COVID-19 Resources Center [30].The daily testing data is available at the Ministry of Health dashboard and Our World group in Data website [29,31]. Data were incorporated until 4th August 2020.

2.2. Modified SEIR mathematical model

To study the impact of different potential country based interventions, this research represented the effects of control measurements and interventions as change points in COVID-19 spreading rate. Based on the epidemiological feature of COVID-19 and the country based intervention applied by Saudi authorities, this study extended the classical 'Susceptible-Exposed-Infected-Removed' (SEIR) to illustrate the transmission of COVID-19 in Kingdom of Saudi Arabia. The modified SEIR conceptual framework has an extra classes "I_c" represents critical cases and "I_t" represents tested infected cases.

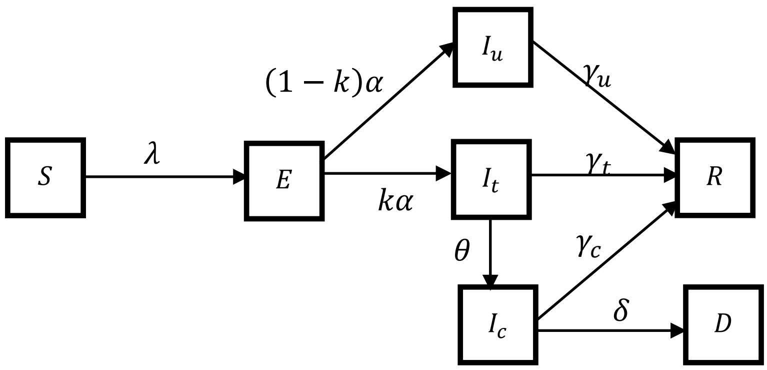

Figure 2. The modified SEIR COVID-19 Compartment Model for of Saudi Arabia.

In the proposed modified model S, E, D and R represent the susceptible, exposed, dead and recovered respectively. While I_u, I_t *and* I_c represent untested infected cases, tested infected cases and critical cases correspondingly. The study assumed that I_u contains Infected cases with mild or no symptoms and hence they are not the infected cases that will die. I_u individuals move to recovered state after the infection period. Recovered state R comprises individuals survived COVID-19 disease. Dead state D contains the individuals have not survived COVID-19 disease.
As the health authorities in Kingdom of Saudi Arabia emphasis on expanding testing capacity and contact tracing, the I_t numbers is expected to increase rapidly. The study considered several control measurements and interventions after the beginning of COVID-19 spread to validate to what extent the implemented interventions had led to a change in COVID-19 spreading rate.

The modified SEIR model has seven states; the first state is susceptible individuals (state S). Susceptible individuals become infected cases with the force of infection λ and move to the exposed state E. Exposed state E represents individuals experiencing incubation period and has no visible clinical signs. At rate α, exposed cases move to I_u *or* I_t based on rates $(1-k)$ and k *and* respectively. The individuals of infected cases group I_u are unrecognized infected cases; they are not necessarily asymptomatic or mild. Consequently, the value of k is mainly affected by the intensity of testing. Untested infected cases recover undiagnosed at rate γ_u, while tested infected cases recovered diagnosed and moves to state R at rate γ_t. Critical cases are diagnosed and recovered at rate γ_c or die at rate δ.

The total population size $N(t) = S(t) + E(t) + I_u(t) + I_t(t) + I_c(t) + R(t) + D(t)$. For simplicity, the study considers the total population size N is constant and neglects the new births and death. Hence, the population $N(t)$ remains unchanged as described in Eq (2.2):

$$\frac{d(S+E+I_u+I_t+I_c+R+D)}{dt}=0. \quad (2.2)$$

The spreading rate function of the modified SEIR model is based on a modified version of spreading function presented in [32,33].

The modified SEIR model for COVID-19 transmission can be defined by the following system of ordinary differential equations (2.3):

$$\begin{aligned}
\frac{dS}{dt} &= -\lambda S(t),\\
\frac{dE}{dt} &= \lambda S(t) - \alpha E(t),\\
\frac{dI_t}{dt} &= k\alpha E(t) - \gamma_t I_t(t) - \theta I_t(t),\\
\frac{dI_u}{dt} &= (1-k)\alpha E(t) - \gamma_u I_u(t),\\
\frac{dI_c}{dt} &= \theta I_t(t) - \gamma_c I_c(t) - \delta I_c(t),\\
\frac{dR}{dt} &= \gamma_t I_t(t) + \gamma_u I_u(t) + \gamma_c I_c(t),\\
\frac{dD}{dt} &= \delta I_c(t).
\end{aligned} \quad (2.3)$$

The study integrated the impact of country based interventions into the modified model by presenting flexible control measurements (CM) and change points in the spreading rate λ. Throughout COVID-19 epidemic in Saudi Arabia, country based interventions implemented in several stages such as quarantine, social distance, schools closure, suspending travels, reducing crowds, people movement restrictions, self-isolation and contact tracing. The aim of these country interventions was to mitigate COVID-19 spreading rate λ. As soon as the spreading rate λ turn into less than one the daily infected cases reduces. The study started with an initial spreading rate λ_0 as the exponential growth rate and up to several vital change points motivated by country based control measurements and interventions.

The spreading rate λ is calculated using Eq (2.4):

$$\lambda = \beta_1\ (1-CM_1)\frac{E}{N} + \beta_2(1-CM_2)\frac{I_u}{N} + \beta_3(1-CM_3)\frac{I_t}{N}. \quad (2.4)$$

where the parameters $\beta_1, \beta_2\ and\ \beta_3$ represent the effective contact rate for E, I_u and I_t respectively. $CM1, CM2\ and\ CM3$ are the control measurements for E, I_u and I_t respectively and $0 \leq CM1, CM2, CM3 \leq 1$. The spreading rate λ integrate the effects of country based interventions.

Based on the above modified SEIR model and using algebraic manipulation, the study calculated the reproducibility rate R_0 as the average value of new infections caused by one individual. Reproducibility rate R_0 is a vital sign of occurrence of epidemic, as $R_0 > 1$ indicates an epidemic. R_0 is defined using Eq (2.5):

$$R_0 = \frac{\lambda}{\mu}, \tag{2.5}$$

where λ is the spreading rate and μ is the recovery rate. The recovery rate is defined by Eq (2.6):

$$\mu = \gamma_u + \gamma_t + \gamma_c, \tag{2.6}$$

R_0 is derived from the proposed system equations as described by Eq (2.7):

$$R_0 = \frac{\beta_1(1 - CM1)}{\alpha} + \frac{\beta_2(1 - k)(1 - CM2)}{\gamma_u} + \frac{\beta_3 K(1 - CM3)}{\gamma_t + \theta}. \tag{2.7}$$

To measure the impact of potential interventions, the study focuses on the actual growth of effective infections with and without the intervention. At the beginning of COVID-19 outbreak the infected cases and recovered cases numbers were small compared to the total population size N_0 and hence the number of daily active cases is estimated using exponential growth spreading rate $\lambda' = \lambda - \mu$.

The modified SEIR model for the transmission dynamics of COVID-19 has several parameters. Some parameter values have been collected from the literature. Other parameters that depend on the population under the study were estimated. Biological interpretations of the modified SEIR model parameters are described in Table 1.

Table 1. Model parameters setting.

Parameter	Notation	Value	Reference
Initial population size	N_0	4218169	[34]
Reproduction number	R_0	2.7	[24,35]
Contact rate for the exposed set	β_1	0.1818	[36]
Contact rate for the untested infected set	β_2	1.86	[37]
Contact rate for the tested infected set	β_3	*1.66*	[37]
Transition rate of exposed E	α	*0.27*	[37]
Case detecting rate	k	*0.2*	*Estimated*
Recovery rate of I_u	γ_u	*0.1*	*Estimated*
Recovery rate of I_c	γ_c	*0.15*	*Estimated*
Recovery rate of I_t	γ_t	*0.1818*	[38]
Rate of I_t moves to I_c	θ	*0.2*	*Estimated*
Death rate of I_c	δ	*0.05*	*Estimated*

3. Results and discussions

The following subsections presents the experimentation and simulation results.

3.1. Model fitting

The study measured the modified SEIR model spreading rate λ by fitting the model estimates to the data of daily and cumulative confirmed cases in Saudi Arabia.

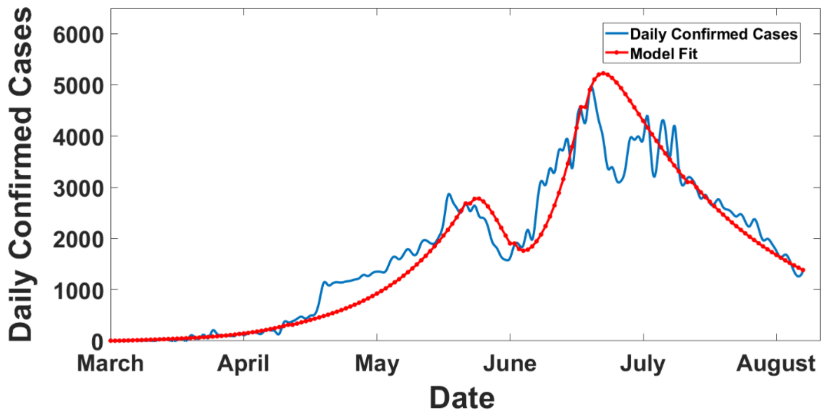

Figure 3. Daily Confirmed Cases Model Fitting.

In the fitting process, the study considered the least square method [39–41] to tackle the error between daily official cases and confirmed cases estimated by the modified SEIR model.

As shown in Figure 3, the blue line represents to the real data obtained from official Saudi reports while the red line has been estimated by solving the modified SEIR mathematical model numerically, using the Matlab software with ode45 tool.

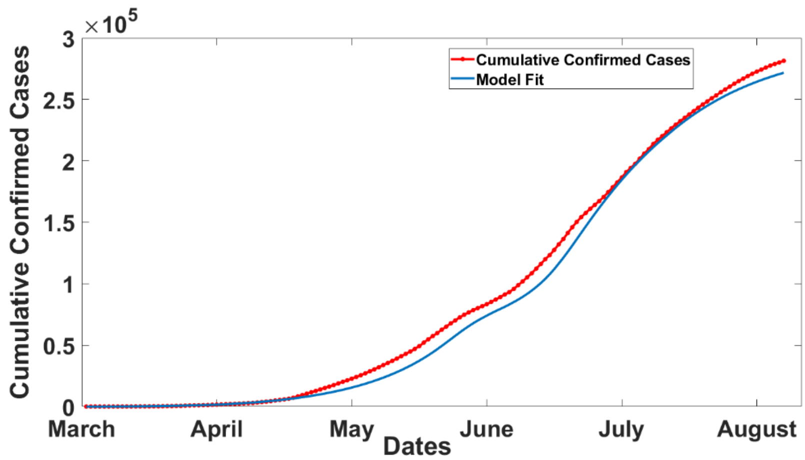

Figure 4. Cumulative confirmed cases model fitting.

In Figure 4, the red line corresponds to the cumulative confirmed number of COVID-19 cases and the blue curve corresponds to the modified SEIR model fit. Robustness of the modified SEIR model is demonstrated by validation against actual infected cases numbers, proving that the parametrization is acceptable.

3.2. Interventions strategies

The study considered a number of control measurements and intervention strategies: quarantine, social distancing, school closure, suspending travels, reducing crowds, people movement restrictions, self-isolation and contact tracing. The experiments considered these control measurements independently and in several combinations. Each of these experiments was measured over time and compared to the baseline scenario in an effort to quantify their impact for decreasing the outbreak. Scenarios are compared in terms of number of confirmed cases, growing rate, peak time, and death rates. Suspension of all international flights is enforced on 15 March 2020 when the number of confirmed cases was 118. Suspension of all international flights is included in modeling of all other control measurements, and is not studied independently. The impact of this control measurement is scientifically proved in several previous studies [42,43]. The confirmed infected cases isolation control measurement was modeled based on the research by Ferguson et al. [44] that confirmed infected cases stay at home, decrease the non-household contacts by 75%. Hence, confirmed infected cases isolation control measurement reduces COVID-19 transmission to 25% of the baseline scenario while the household contact rate is unaffected. The home quarantine control measurement like the isolation strategy reduces the non-household contacts to 25% of the baseline scenario whereas the in-household contacts rate is doubled [45]. To represent the effect of social distancing, the proposed model eliminates all working group contacts and defining the non-household contacts to be 50% of the baseline scenario while the household contact rate is unchanged. However, social distancing levels differ from non-social distance state 0% to full lockdown state 100%. Modeling school closures decrease teaching staff and students contacts to 0%, nonetheless increase the contacts rate within households. School closures increase the household contacts rate with a 50%.

The study started with an initial spreading rate λ_0 as the exponential growth rate and up to several vital change points motivated by country based control measurements and interventions.

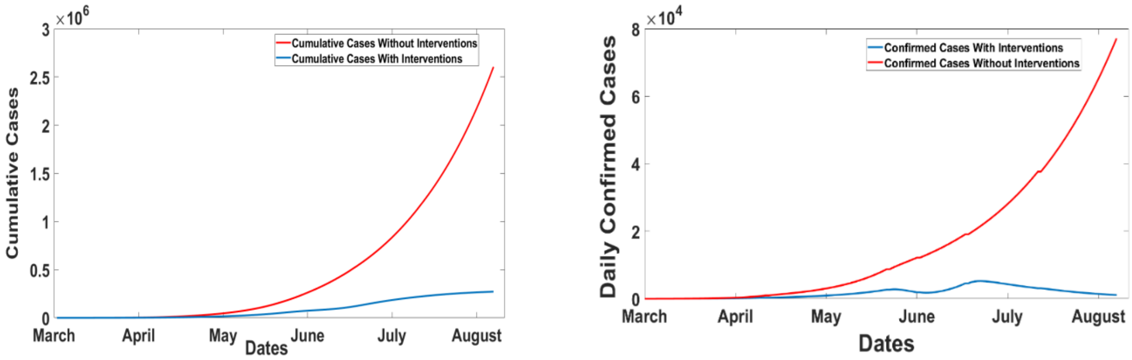

Figure 5. Daily and cumulative confirmed cases with and without interventions.

Considering the baseline scenario as shown in Figure 5, with hard epidemic peaks occurring about the end of July 2020 in the absence of any control measurements. The scale of the outbreak effect is very high, around 3 million infected cases of the Saudi population. As shown in Figure 5 the results show that the country based interventions are effective in reducing daily and cumulative infected cases population. By introducing the interventions, the cumulative infected cases population is reduced from 2.6 million to less than 271,000 at the end of the study period. Hence, implementing interventions in Saudi Arabia is capable of decreasing the effects of an epidemic by flattening the curve and decreasing the infected cases population peak.

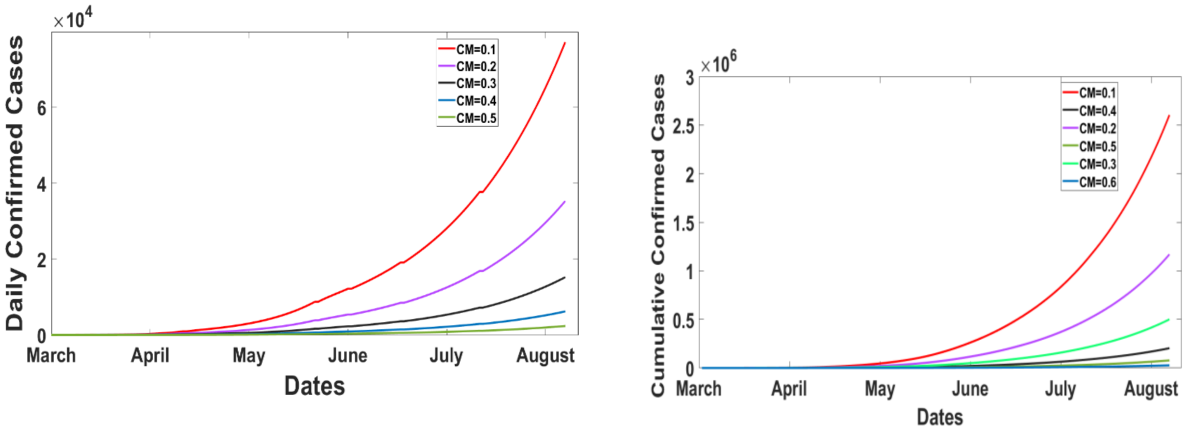

Figure 6. Daily and cumulative confirmed cases with different interventions.

The study conducted several of experiments to estimate the number of confirmed cases as well deaths in Saudi Arabia for different country based control measurements using the proposed model starting from March 2nd, 2020 till August 4th, 2020 (156 days).

Daily confirmed cases, cumulative confirmed cases and deaths under different control measurements (CM) $(CM = 0.1$, $CM = 0.2$, $CM = 0.3$, $CM = 0.4$, $CM = 0.5)$ in Saudi Arabia during the mentioned period are presented in Figures 6 and 7.

As shown in Figure 6 country based interventions with $CM = 0.5$ can significantly reduce the confirmed infected cases population and postpone the peak number of infected cases. A large epidemic can be prevented if the CM of these interventions exceeds 0.3 $(CM \geq 0.3)$. For CM less than 0.2 the interventions reduce the peak number of confirmed infected cases and spread rate but still the number of cumulative confirmed cases (1.1 Million) is high.

As shown in Figure 7, by increasing the control measurements CM from 0.1 to 0.5 the peak of cumulative death is reduced from 120 thousands to 5 thousands at the end of the study period. The intervention implemented in Saudi Arabia to control the spread of the novel COVID-19 reduced the impact of the epidemic and flattened the death curve and reduced the fatality rate. Whereas the cumulative confirmed cases population may grow over a longer period, the final fatality rate is reduced at the end.

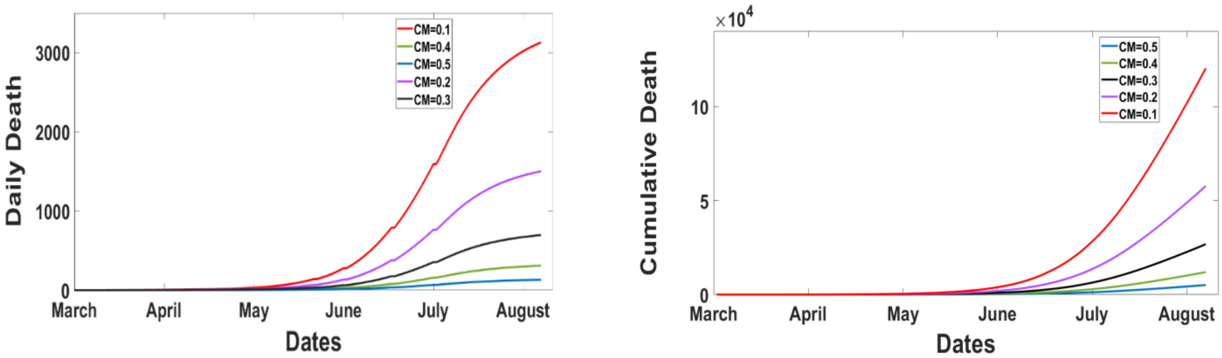

Figure 7. Daily and cumulative death with different interventions.

3.3. Expanding testing capacity

One of the main policies implemented by Saudi authorities is testing capacity expansion. Figure 8 shows the increase of number of testing in Saudi Arabia starting from the 5th May 2020.

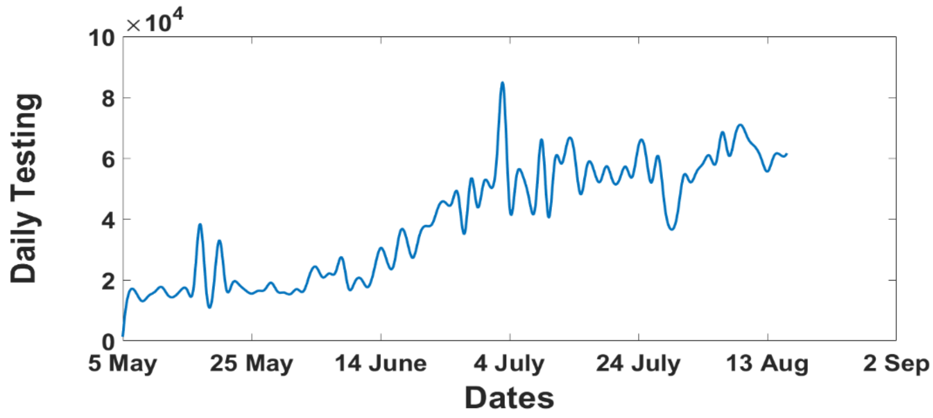

Figure 8. Daily testing numbers in Saudi Arabia.

Figure 8 shows the rapid increase in testing numbers from 16,026 on the beginning of May to 61,620 on 20 August 2020. Worth mentioning, isolating the confirmed cases contacts from their social networks, and considering the pre-symptomatic and asymptomatic spread of COVID-19 assumed to be one of the significant factors that decrease the spreading rate.

The following figures describe the effect of expanding testing capacity.

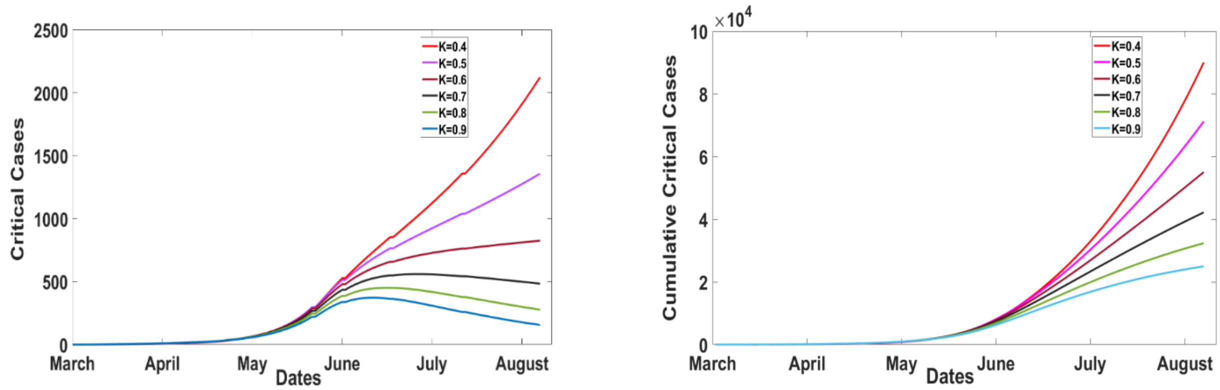

Figure 9. Daily and cumulative critical cases with different testing.

Worth mentioning, isolating the confirmed cases contacts from their social networks, and considering the pre-symptomatic and asymptomatic spread of COVID-19 assumed to be one of the significant factors that decrease the spreading rate.

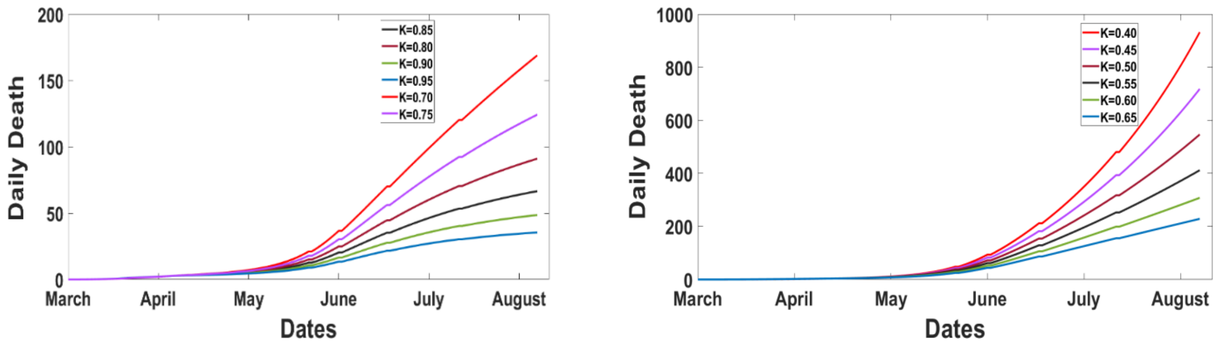

Figure 10. Daily death with different testing.

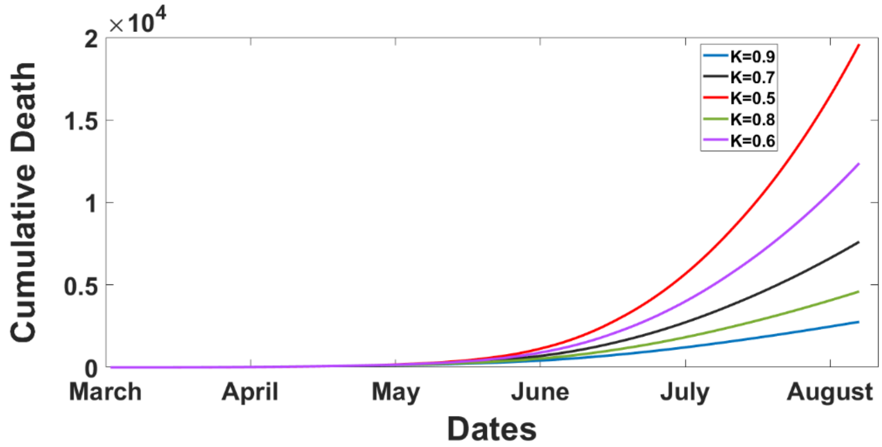

Figure 11. Cumulative death with different testing**.**

Daily critical cases and deaths under different testing ratio $(k = 0.4,\ k = 0.5,\ k = 0.6,\ k = 0.7,\ k = 0.8,\ k = 0.9)$ in Saudi Arabia during the stated period is depicted in Figures 9–11. The results show that in all cases when increasing the testing rates, the spread of COVID-19 has been successfully controlled and has no peak time. In case of testing rate $k = 0.1$, the estimated accumulative death is 19,595. When increasing the testing rates to $k = 0.9$, the accumulative death decreased to 2760. Regarding critical cases, increasing testing ratio from $k = 0.4$ to $k = 0.9$ reduces the estimated critical cases from 24,937 to 9028. This result reveals that expanding testing capacity has effective impact in contact tracing and case isolation control of COVID-19 epidemic.

3.4. Model predictions

The study proceeds to short-term forecasts of daily confirmed cases assuming that the control measurements are continued. Figure 12 shows estimates of short term forecasts till 7 October 2020. As depicted in the Figure 12 the daily confirmed cases will continue in steady cases around 1000 cases per day until end of August. Starting from the first day of September the daily cases decreases slowly until it reaches around 600 cases per day at the end of October 2020.

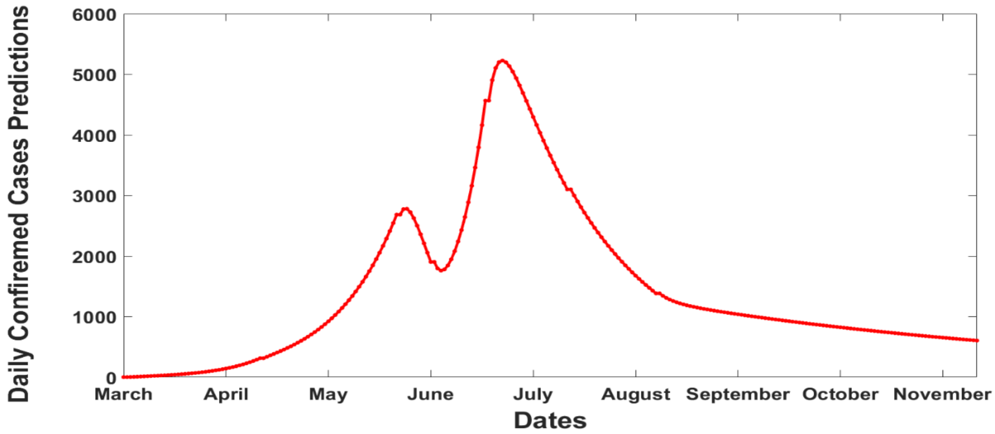

Figure 12. Daily confirmed cases predictions.

3.5. Limitations of research

The study mainly considered the confirmed cases and does not focus on the possible decrease in transmission from asymptomatic undiagnosed cases. The decrease rate of spreading of undiagnosed cases is still under investigation. Furthermore, the lake of adequate data limits the process of asymptomatic cases spreading reduction rate estimation. Additionally, the study assumes that the population distribution within the country is homogeneous. Therefore, the geographical distribution of the outbreak within the country is not considered.

4. Conclusion

The study proposed a modified SEIR mathematical model focusing on testing capacity expansion and number of critical cases. The modified model was fitted and assessed with Saudi Arabia dataset contains the confirmed cases, recovery and death cases. This paper examined different control measurements scenarios produced by the modified SEIR mathematical model. The experimental findings show that by increasing the control measurements from 0.1 to 0.5 the peak of cumulative death is reduced from 120 thousands to 5 thousands at the end of the study period. Hence, the studied findings show that the intervention implemented in Saudi Arabia to control the spread of the novel virus reduced the impact of the epidemic and flattened the death curve and reduced the fatality rate. In conclusion, the research established a modified SEIR model, which allows to study the impact of testing expansion and social distances interventions. The results revealed that regardless of the significant effect of social distancing and increasing testing capacity, it is unlikely that the control of the COVID-19 outbreak could be achieved without control measurements and interventions.

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Conflict of interest

The authors declare that there is no conflict of interest.

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