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# Generalized Susceptible–Exposed–Infectious–Recovered model and its contributing factors for analysing the death and recovery rates of the COVID-19 pandemic

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## ABSTRACT

COVID-19 is a highly contagious disease that has infected over 136 million people worldwide with over 2.9 million deaths as of 11 April 2021. In March 2020, the WHO declared COVID-19 as a pandemic and countries began to implement measures to control the spread of the virus. The spread and the death rates of the virus displayed dramatic differences among countries globally, showing that there are several factors affecting its spread and mortality. By utilizing the cumulative number of cases from John Hopkins University, the recovery rate, death rate, and the number of active, recovered, and death cases were simulated to analyse the trends and patterns within the chosen countries. 10 countries from 3 different case severity categories (high cases, medium cases, and low cases) and 5 continents (Asia, North America, South America, Europe, and Oceania) were studied. A generalized SEIR model which considers control measures such as isolation, and preventive measures such as vaccination is applied in this study. This model is able to capture not only the dynamics between the states, but also the time evolution of the states by using the fourth-order-Runge–Kutta process. This study found no significant patterns in the countries under the same case severity category, suggesting that there are other factors contributing to the pattern in these countries. One of the factors influencing the pattern in each country is the population's age. COVID-19 related deaths were found to be notably higher among older people, indicating that countries comprising of a larger proportion of older age groups have an increased risk of experiencing higher death rates. Tighter governmental control measures led to fewer infections and eventually reduced the number of death cases, while increasing the recovery rate, and early implementations were found to be far more effective in controlling the spread of the virus and produced better outcomes.

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## 1. Introduction

The World Health Organization (WHO) [1] defines a pandemic as a worldwide spread of a new disease. In early 2020, a new disease, the novel coronavirus disease (COVID-19) began to circulate to every part of the world. It was initially detected in Wuhan, China in December 2019 and was eventually declared a pandemic by the WHO [2] on 11 March 2020. As of 31 March 2021, more than 128 million people have been infected by this disease, with a total recovery of 104 million cases and a total of almost 2.8

million deaths worldwide [3]. This highly transmittable and confirmed rapid human to human transfer of the disease coupled with the fact that no vaccine has yet been found is not putting the ever-increasing number of infections and deaths worldwide to a halt. Since the virus can be transmitted through close contact by way of respiratory droplets produced when someone coughs, sneezes, or talk [4], it is no wonder that this disease is spreading like wildfire. With a  $R_0$  possibly as high as 5.7, which means that for every person infected, another 5.7 person will be infected by that 'patient zero', it seems that this pandemic is nowhere near the end since an  $R_0$  of less than 1 is required for the disease to progressively disappear (Sanche et al. [5]). Dur-e-Ahmad and Imran [6] applied data from countries that were most affected countries by COVID-19, namely China, Iran, South Korea, and Italy

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and fitted this into a SEIR type model to estimate the basic reproduction number  $R_0$ . This study found that the  $R_0$  value is highly dependent on the contact rate among the infected individuals. It was observed by Fanelli and Piazza [7] that the spread of COVID-19 in a few countries were consistent with each other, suggesting that there are some common trends in the spread of the epidemic within each country. In China, it was found that the average time span between the emergence of symptoms and death was 17.8 days, and the duration for recovery was 24.7 days (Verity et al. [8]).

Historically, many pandemics have plagued this world before. Some of the notable ones from the last century would be the 1918 Spanish Flu and the Asian Flu which occurred in the late 1950s [9]. Pandemics that occurred in this century include the Swine Flu pandemic caused by the H1N1 virus and of course, the currently ongoing COVID-19 pandemic. The severity of each outbreak differs from each other and is measured using its overall mortality rate. The 2009 H1N1 pandemic mostly attacked the younger individuals as they did not have an immunity against the disease, unlike the older people. The global mortality rate for this pandemic was at an estimated 0.001% to 0.007% of the worldwide population during the first year of the virus circulation [10]. Another notable pandemic that occurred previously would be the 1918 influenza pandemic, AKA the Spanish Flu [11]. It is rated as the most severe pandemic in recent history, spreading worldwide for about two years, infecting roughly a third of the global population at that time, and killing an average of 50 million people in total [11]. Between 1957–1958, the world faced the Asian Flu pandemic, caused by the H2N2 virus which emerged in East Asia and took the lives of 1.1 million people [12]. The Ebola disease circulated between 2014 and 2016, mostly in West Africa, and about 11,325 deaths were reported [13]. The severe acute respiratory syndrome (SARS) emerged in February 2003 and infected people between the age of 25 and 70 [14]. The case fatality rate (CFR) of SARS was estimated to be at 3% [14]. The Middle East Respiratory Syndrome (MERS) appeared in Saudi Arabia in 2012 and its patients are ranged between 1 and 99 years old [15]. The CFR rate for MERS was found to be at a whopping 34.4% [15]. In conclusion, it is quite clear that the most severe pandemic to have ever occurred before COVID-19 would be the 1918 influenza pandemic. Hence, this study will exhibit the impacts of this pandemic based on its death and recovery rates within 10 countries, which will give us an idea of where it will stand in the history of pandemics in terms of severity.

Besides this, the factors that affect mortality rates such as age, gender and pre-existing health conditions will also be discussed. According to the publicly available data from Worldometer [16], the age group with the highest number of deaths in New York were those aged 75 years and above, comprising of almost half of the share of deaths in New York City. Of course, these patients were more susceptible to the disease as most of them were already battling other underlying health conditions such as chronic diabetes, hypertension, and cardiovascular diseases. It was also shown that the number of male deaths was significantly higher than female deaths, constituting a whopping 61.8% of the share of deaths. This may be due to several reasons, one of it being the more common habit of smoking and alcohol drinking among males. Sanyaolu et al. [17], Richardson et al. [18], and Guan et al. [19] found that comorbidities were present in many COVID-19 patients and most of them were above the age of 60. Patients with diabetes, hypertension and cardiovascular diseases had a higher chance of contracting the disease due to their weakened immune system and had a greater likelihood in developing a more chronic progression of the disease. Age is also a major factor that affects the mortality rates during a pandemic and should be included in the forecast of a country's infection, morbidity, and

mortality rates. A study on the COVID-19 cases in Portugal by Nogueira et al. [20] supports the theory that younger individuals are less susceptible to the disease. There was no excess mortality compared to the normal day mortality for those under 55 years of age. A study by Wong et al. [21] also supported this theory by showing that those aged 65 years and above accounted for roughly 80% of the total deaths in the Hong Kong influenza pandemic. This theory, however, is not always true for every pandemic that occurred. According to Gagnon et al. [22], during the 1918 Spanish Flu, young adults between the ages of 20 and 40 had the highest mortality rate, probably due to their exposure to the strain of influenza during the Russian Flu Pandemic that took place in early stages of their life between 1889–1890. Another important factor to take note of in forecasting mortality would be comorbidities. The mortality risk for those who were older and had underlying health conditions was higher than those without (Banerjee et al. [23]). Gender is also a significant factor that influenced the mortality risk of a person. Jin et al. [24] discovered that for both the COVID-19 and SARS pandemics, both genders were equally susceptible but the severity of the disease in male patients tend to be more critical than that of the female patients. A longer duration of exposure to the disease is another cause of a surge in death cases. For example, Verma et al. [25] found that a mere extra 3 to 10 days of lethal exposure in Spain, Italy and Iran could result in a drastic hike to a 10% mortality rate.

As mentioned earlier, the COVID-19 outbreak has infected more than 128 million people worldwide and has taken the lives of more than 2.8 million people [3]. On a brighter note, more than 104 million people have recovered from this disease, reflecting a 97% overall recovery rate [3]. However, there have been positive cases among discharged COVID-19 patients in China (Li, Zhang and Zong, [26]). According to the WHO [27], there is not enough evidence to prove that people are immune to a second infection of COVID-19. This means that those who recovered from COVID-19 can still fall victim to the disease again. Therefore, we are yet to observe a drop in global mortality rates as the only measure that is helping to curb the spread of this disease are the governmental implementations of social distancing, which relies heavily upon the compliance of the people. Today, USA has the highest number of infections and deaths, with a death rate of 1.81%, followed by Brazil and Mexico, with a death rate of 2.51% and 9.07% respectively [3]. The number of infections and deaths seem to be increasing exponentially and is not slowing down anytime soon. Thus, the confirmed, death and recovery rates of this pandemic, and the factors that contribute to the changes in these rates will be analysed in this study.

Having said that, a generalized Susceptible–Exposed–Infectious–Recovered (SEIR) model will be used to assess the death and recovery rates alongside the confirmed cases of COVID-19 of ten countries from different continents with different levels of infections. This model was chosen as it was found to be appropriate in measuring the spread of COVID-19 according to proposed scenarios (Anastassopoulou [28]). The malleability of the SIR model is a great advantage as it allows the model to adjust the fitting of parameters (Becker & Grenfell [29]). The SIR model is not only able to predict the infection rate of COVID-19 but also the mortality and recovery rates, (Al-Raei [30]). Some studies even used this model to forecast the endpoint of the outbreak (Jia et al. [31]). This study will also discuss the significant impacts of age, gender and comorbidity on the case fatality rates (CFR) of the relevant countries. The effectiveness of the control measures on the changes in the basic reproduction number,  $R_0$  over time will be displayed graphically, and the type and stringency of the implementations will be matched with the changes in the  $R_0$  values.

When a pandemic occurs, decisions made by the government can make or break the country. In this case, this highly contagious disease spreads through social contact and it is therefore highly essential to practice social distancing which is already implemented by many countries worldwide. Kraemer et al. [32] found a strong correlation between human mobility and the COVID-19 growth rate as the growth rate in China plummeted after strict control measures were enforced. Yang et al. [33] used the Susceptible–Exposed–Infectious–Recovered (SEIR) model to obtain the COVID-19 epidemic curve in China. It was found that regions with quarantine control experienced slower epidemic growth than those without, supporting the efficacy of quarantine and control measures. This fact is supported by Thunström et al. [34] who proved that a reduction in social contact by 38% can halve the infection curve of a country. However, there are also some who observed contradictory results to this where social distancing only shifts the peak of infection to a later date instead of shrinking it. Matrajt & Leung [35] proved that the timing of interventions had a great impact on the epidemic curve. They discovered that later interventions were more successful in flattening the epidemic curve, whereas early interventions may only delay the epidemic curve from heightening instead flattening it permanently because the number of susceptible persons had not changed. Having said that, this COVID-19 pandemic has a lower-case fatality rate (CFR) compared to previous seasonal flus such as the SARS and MERS pandemics (Khafaie and Rahim [36]).

Eventually, the situation is bound to return to normal. But it remains to be seen when it will be truly safe for us to step out without having the risk of getting infected by this disease that has drastically changed everyone's lifestyle. Fernández-Villaverde & Jones [37] discussed the potential easing of social distancing leading up to the building of a herd immunity. However, this would only be a good step for regions with a high infection rate and low mortality rate. This study seeks to analyse the current effects and possible aftermath of this unforeseen pandemic in terms of the death and recovery rates as well as the significant factors that may limit or elevate an individual's chances of survival within the ten countries chosen for this study. Hence, this study aims to help the public understand the meaning behind the figures portrayed in the number of confirmed cases, deaths, and recoveries. Publicly available data may make these numbers accessible, but they do not explain the trends and characteristics of the epidemic in each country and the reasons behind any similarities or a complete disparity. Also, there are vague discussions and mere assumptions on the factors that contributes to the spread and susceptibility to COVID-19. Therefore, this study will simulate the COVID-19 death and recovery rates, as well as the number of cases of the 10 countries using the generalized SEIR model. The results obtained will then be analysed and discussed alongside the contributing factors. The findings of this study can be utilized by the public and the government to develop better awareness about the virus in order to mitigate the risks associated with the virus and develop suitable mitigation plans to curb the epidemic within the country. For instance, age, gender, and underlying health conditions were found to play a significant role in determining the severity of the pandemic within a country. Therefore, health authorities can use these findings to implement a more stringent ruling for these specific groups. This is vital as it was also deduced that control measures that were taken by the government significantly reduced the basic reproduction number,  $R_0$ , which led to fewer numbers of cases and eventually increased the recovery rate and lowered the death rate. The time factor coupled with stringent efforts taken by the government is also significant in preventing the infection numbers from increasing out of control. As a case in point, one of the countries studied prioritized these two factors, and zero infected cases were achieved within a few months.

The rest of this paper is organized as follows. Section 2 reviews the basics of the model used in this study, which is the generalized Susceptible–Exposed–Infectious–Recovered (SEIR) model. Section 3 will lay out the process of obtaining the datasets, the framework of the models used, and the formulae used to compute the parameters in the model. Section 4 will present the factors affecting the susceptibility to COVID-19, and how the control measures implemented in each country affects the spread of this virus. Section 5 will present and discuss the results of this study where the trends of the number of cases, deaths, and recoveries in the 10 chosen countries obtained using the SEIQRDP model will be analysed. The later part of this section will exhibit a country-specific analysis on the case fatality rate (CFR) for each factor, and how the control measures implemented in each country influences the overall spread of the virus. In Section 6, the concluding remarks which includes the summary of the main contributions of this study, the limitations of this study, and the recommendations for future studies will be presented. This will be followed by the acknowledgements and the list of references.

## 2. Preliminaries

This section reviews the rudimentary aspect of the model used in this study, which is the generalized Susceptible–Exposed–Infectious–Recovered (SEIR) model. This compartmental model which models the transmission of dynamics of infectious diseases was developed in the early 20th century with the most notable work by Kermack and McKendrick [38]. This model was chosen over others due to its flexibility. It can be adjusted according to the dynamics of the epidemy by adding or dropping certain components such as the addition of isolation and vaccination states into the model (Weiss [39]). This model aimed to predict the spread of a disease, the length of an epidemic, the total number of infected cases, and to estimate various epidemiological parameters such as the reproductive number. Over time, the compartmental model for epidemics developed to account for many variables. When considering diseases such as influenza, for example, an incubation period is introduced, that is, when a person is infected but not yet infectious. This stage of latency is known as the 'Exposed' stage. This model is called the SEIR (Susceptible–Exposed–Infectious–Recovered) model (Anderson & May [40]; Hethcote [41]). Just like any other compartmental models, for simplicity, certain assumptions about this model such as a constant population number ( $N$ ), constant rates, and a well-mixed population were made (Jones [42]).

With a similar analogy, the SEIR model continues to develop over time to consider the changing dynamics of an epidemic. Using a mathematical model based on dynamic equations, various control measures such as vaccination could be assessed, which could provide essential information on the dynamics of the epidemic and is particularly helpful when basic epidemiological parameters are largely uncertain due to its development over time (López & Rodo [43]). Studies in South Korea (Fang et al. [44]) and Taiwan (Wu & McGoogan [45]) where the countries deployed aggressive contact tracing and quarantine systems (Li et al. [46]) showed that they could control not only the infection within the population but also the growing proportion of undiagnosed infections that eventually occurs. Therefore, it is crucial to evaluate the effects of the social distancing actions imposed by governments, mandatory self-isolation, and other preventive measures to model the epidemics more accurately (López & Rodo [43]).

As the COVID-19 case count as well as its case fatality rate continues to increase, the death rate of COVID-19 will become more alarming and will not only impact us now, but also in the near future. Thus, it is vital to analyse its spread and its causation as well as negating factors, to be able to make effective decisions, not only for the healthcare systems but also

**Table 1**  
The categorization of countries.

Level of severity	Continent			
	Asia	Europe	North/South America	Oceania
High	India	Russia	Brazil	–
Medium	Japan	Portugal	Canada	–
Low	Cambodia	Iceland	Barbados	New Zealand

**Table 2**  
The number of confirmed cases for each country as of 28 February 2021.

Country	Number of confirmed cases
India	11,112,241
Russia	4,198,400
Brazil	10,551,259
Japan	432,090
Portugal	804,562
Canada	871,622
Cambodia	820
Iceland	6049
Barbados	3068
New Zealand	2378

in governmental planning for the changing needs of the society (Janssen [47]). Social distancing, population demography, underlying health conditions, and other factors would determine the length and severity of this pandemic. Hence, it is imperative for us to use reliable data for an up-to-date result to effectively visualize the outcome of this outbreak. The generalized SEIR model has been chosen to model the death and recovery rates of COVID-19 in 10 countries as it has been proven to be the most suitable and reliable model in analysing the changes within these rates using the concept of derivatives (Al-Raei [30]; Fernández-Villaverde & Jones [37]). Therefore, this study is based on the SEIQRDP model that considers the effects of self-isolation and other preventive measures and utilizes an open-source MATLAB code that was developed by Cheynet [48]. This model introduced additional states to better capture the dynamics of the COVID-19 epidemic such as quarantined state and unsusceptible state which are portions of the population that are immune to the virus.

### 3. Methodology

The datasets used in a study is one of the most vital parts of the research. It is crucial for us to select reliable and trustworthy sources, so accurate results can be produced. The main source of data used in this study is the COVID-19 data repository from the John Hopkins University, Center for Systems Science and Engineering (JHU CSSE) [49]. This section will lay out the process of obtaining the datasets, the framework of the models used, and the formulae used to compute the parameters in the model.

#### 3.1. Datasets

This section will discuss the datasets used in this study, the source of the data used, the processing of the data and the method of dealing with missing data within the datasets. Ten countries from different continents and different levels of severity to the pandemic were chosen for this study. For each level, the countries were chosen from three different continents – Asia, Europe, and North/South America. The level of severity to the pandemic was defined by the number of confirmed cases as of the 28th of February 2021. The high level indicates that the country has over a million cases, the medium – between 10,000 and a million cases, and the low level means that the country has had below 10,000 cases so far. The summarized information for each country is displayed in Tables 1 and 2.

#### 3.1.1. Source and duration of data

The data used in this study were extracted from reliable sources to ensure the accuracy of the results. Table 3 displays the type of data used in this study, the period of the data used, and its sources.

#### 3.1.2. Data pre-processing

The numbers for the daily confirmed, deaths, and recovered COVID-19 cases obtained from the JHU repository were straightforward and complete. The daily cumulative data for each country from 22 January 2020 to 28 February 2021 were utilized. No missing or duplicated data were found. The vaccination rate for each country were acquired from the Our World in Data [50] website which allowed us to extract the rates from their interactive dashboard. The rates derived were defined as the daily dose administered per 100 people and was a rolling 7-day average. The starting date of vaccination for each country differed from each other, but the end date was standardized to the 28th of February 2020. Next, the basic reproduction number,  $R_0$  was obtained from the JHU COVID-19 data repository on Github. The average of the daily  $R_0$  values available for each country was extracted. Again, the starting date for the data available for each country differed from each other, but the calculation was stopped on 28 February 2020. According to the WHO, the incubation period for the virus had an average of between 5 to 6 days but may take up to 14 days [51]. Hence, the larger value of the average was taken. The total population of the countries as of 1st March 2021 were used in this study, one day after the end of the period of study. The daily stringency index for each country acquired were also complete and had no missing data points for any of the dates between the starting and ending point of the period (see Table 4).

### 3.2. Important formulae

This study adopts a generalized SEIR (Susceptible–Exposed–Infectious–Recovered) model with seven states and eight parameters to perform a mathematical computation to interpret the available data of the cumulative COVID-19 confirmed, death, and recovered cases. In this section, the derivation of the SEIQRDP (Susceptible–Exposed–Infectious–Quarantined–Recovered–Dead–Insusceptible) model will be explained and presented. The parameter estimations will also be discussed in this section. The SEIQRDP model implementation is readily available as a package developed by Cheynet [48] in MATLAB. The package is compatible with R2018b and later releases.

#### 3.2.1. The SEIQRDP model

This study is based on the SEIQRDP model that can incorporate various control measures that capture the dynamics of the COVID-19 epidemic such as vaccination and isolation states [54]. The model was then used to interpret available data of COVID-19 cases by simulating each chosen countries’ epidemic using the model and analysing the results. We split the total population into seven compartments/groups: individuals that are susceptible to the virus (S), individuals that are infected by the virus but not yet infectious (E), infective individuals who are not isolated (I), isolated individuals who will not infect others (Q), individuals that have recovered from the virus (R), deceased individuals (D), and vaccinated individuals who are protected from the virus (P). For simplicity, a few assumptions were made. First, we assumed that individuals who tested positive for the virus (I) would undergo isolation and will not infect others (Q). Second, it is assumed that the recovered (R) and deceased individuals (D) are assumed to be no longer susceptible to the virus, and lastly, vaccinated individuals (P) are assumed to be protected permanently from the virus. Denoting at time  $t$ , the seven states are defined as follows:

**Table 3**  
List of data for each country, its period, and its sources.

Data	Period	Source
The daily confirmed, deaths, and recovered COVID-19 cases	22 January 2020–28 February 2021	Johns Hopkins University Center for Systems Science and Engineering (JHU CSSE) [49]
Vaccination rate	Start date: Different for each country. End date: 28 February 2021	Our World in Data [50]
Basic reproduction number, $R_0$	Start date: Different for each country. End date: 28 February 2021	Johns Hopkins University Center for Systems Science and Engineering (JHU CSSE)
Average latent time of COVID-19	-	World Health Organization [51]
Total population, N	As of 1st March, 2021	Our World in Data [52]
Stringency index	22 January 2020–28 February 2021	Oxford COVID-19 Government Response Tracker, Blavatnik School of Government [53].
Type of vaccines used in each country	-	Johns Hopkins University Center for Systems Science and Engineering (JHU CSSE).

**Table 4**  
The period for the vaccination rate and the basic reproduction number,  $R_0$  for each country.

Country	Period of vaccination rate	Period for basic reproduction number, $R_0$
India	16/1/21–28/2/21	15/3/20–28/2/21
Russia	16/12/21–28/2/21	18/3/20–28/2/21
Brazil	17/1/21–28/2/21	14/3/20–28/2/21
Japan	18/2/21–28/2/21	22/2/20–28/2/21
Portugal	28/12/20–28/2/21	14/3/20–28/2/21
Canada	15/12/20–28/2/21	12/3/20–28/2/21
Cambodia	10/2/21–28/2/21	30/2/20–28/2/21
Iceland	31/12/20–28/2/21	13/3/20–28/2/21
Barbados	16/2/21–28/2/21	12/7/20–28/2/21
New Zealand	19/2/21–28/2/21	23/3/20–28/2/21

- (i)  $S(t)$ : Susceptible cases.
- (ii)  $E(t)$ : Exposed cases (infected but not yet infectious).
- (iii)  $I(t)$ : Infectious cases, but not quarantined.
- (iv)  $Q(t)$ : Quarantined cases.
- (v)  $R(t)$ : Recovered cases.
- (vi)  $D(t)$ : Dead cases.
- (vii)  $P(t)$ : Unsusceptible or protected cases.

Just like any other compartmental models, for simplicity, certain assumptions about this model, namely, a constant population number ( $N$ ), constant rates, and a well-mixed population were made (Jones [42]). Summing all the components, we get the total population ( $N$ ) by Eq. (1):

$$N = S(t) + E(t) + I(t) + Q(t) + R(t) + D(t) + P(t) \tag{1}$$

The model considers six parameters that characterizes the dynamics of the epidemic, all of which are summarized as follows:

- (i)  $\alpha$  (alpha) = protection/quarantine rate
- (ii)  $\beta$  (beta) = infection rate
- (iii)  $\gamma$  (gamma) = inverse of the average latent (delay) time/incubation time
- (iv)  $\delta$  (delta) = rate at which infectious people enter quarantine
- (v)  $\lambda(t)$  (lambda) = time-dependent cure/recovery rate
- (vi)  $\kappa(t)$  (kappa) = time-dependent death/mortality rate

The relationship between each state is depicted in Fig. 1:

Over time, the portion of susceptible individuals transformed into unsusceptible individuals through vaccination, so that the portion of susceptible individuals decreased by alpha ( $\alpha$ ) susceptible individuals ( $S$ ) transformed into unsusceptible individuals ( $P$ ) through vaccination. The rate at which susceptible individuals become unsusceptible is the protection/vaccination rate ( $\alpha$ ), and thus, over time, the portion of susceptible individuals decreased by the rate  $\alpha$ , whereas the unsusceptible individuals increase by the rate  $\alpha$ . Susceptible individuals ( $S$ ) who are not protected/vaccinated transformed into exposed individuals ( $E$ ) when they are infected. Suppose that each infectious individual ( $I$ ) comes into contact with a portion of susceptible individuals over the total population ( $\frac{S(t)}{N}$ ) and of these contacts, the susceptible individuals will become exposed, thus the susceptible individuals will decrease at an infection rate ( $\beta$ ) and the exposed individuals will increase at an infection rate ( $\beta$ ). After some time, the exposed individuals ( $E$ ) then transform into infectious individuals ( $I$ ) with the rate denoted by gamma ( $\gamma$ ), which is the inverse of the average latent time or incubation time. Next, infectious individuals ( $I$ ) will enter quarantine where they are assumed to be no longer infectious and transited into quarantined individuals ( $I$ ) with the quarantine rate, delta ( $\delta$ ). Then, quarantined individuals could transform into either recovered or deceased individuals with rates denoted as lambda ( $\lambda$ ) and kappa ( $\kappa$ ) which is the cure/recovery rate and the mortality/death rate, respectively. The dynamics of the model and its relation between each state are governed by a system of equations that are mathematically formulated through ordinary differential equations (ODEs) as follows:

$$(i) \frac{dS(t)}{dt} = -\alpha S(t) - \beta \frac{S(t)I(t)}{N} \tag{2}$$

$$(ii) \frac{dE(t)}{dt} = -\gamma E(t) + \beta \frac{S(t)I(t)}{N} \tag{3}$$

$$(iii) \frac{dI(t)}{dt} = \gamma E(t) - \delta I(t). \tag{4}$$

$$(iv) \frac{dQ(t)}{dt} = \delta I(t) - \lambda(t)Q(t) - \kappa(t)Q(t) \tag{5}$$

$$(v) \frac{dR(t)}{dt} = \lambda(t)Q(t) \tag{6}$$

$$(vi) \frac{dD(t)}{dt} = \kappa(t)Q(t) \tag{7}$$

$$(vii) \frac{dP(t)}{dt} = \alpha S(t). \tag{8}$$

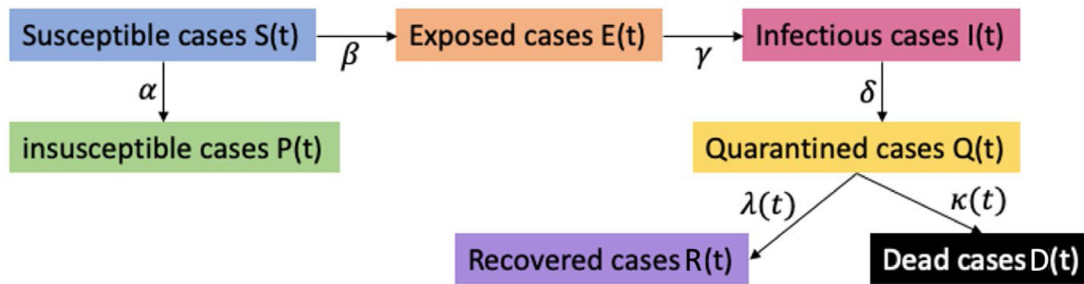


Fig. 1. The interaction between each state in the SEIQRDP model.

Note that summing Eqs. (2) to (8) would result in 0, since a constant population is assumed, thus, a vertical transmission is not possible and the portion from each component will only move within the model. This is consistent with Eq. (1) as differentiating Eq. (1) with respect to time will result in 0 as the derivatives of a constant value would always equal to 0:

$$\frac{dN}{dt} = \frac{dS(t)}{dt} + \frac{dE(t)}{dt} + \frac{dI(t)}{dt} + \frac{dQ(t)}{dt} + \frac{dR(t)}{dt} + \frac{dD(t)}{dt} + \frac{dP(t)}{dt} = 0$$

where  $N = \text{total population of observed country}$ .

The cure rate  $\lambda(t)$  and mortality rate  $\kappa(t)$  are both modelled to be time-dependent. Both rates will be estimated using the open-source MATLAB package that used the general idea of least-squares solution. However, some initial empirical coefficient ( $\kappa_0, \kappa_1, \lambda_0, \lambda_1$  and  $\tau_\lambda$ ) is needed for smoothing these estimated parameters.

To model the time-dependent coefficients  $\kappa(t)$  and  $\lambda(t)$ , the model will automatically fit the coefficient input ( $\kappa_0, \kappa_1, \lambda_0, \lambda_1$  and  $\tau_\lambda$ ) and choose one of the equations for the best approximation. For both parameters, the fitting was done automatically using the 'fit\_SEIRQDP' function in the package to best approximate the mortality rate  $\kappa(t)$  and the cure rate  $\lambda(t)$ . For the mortality rate  $\kappa(t)$ , the package will model the rates using one of the following equations (Eqs. (9) to (11)):

$$(i) \kappa(t) = \frac{\kappa_0}{\exp(\kappa_1(t - \tau_k)) + \exp(-\kappa_1(t - \tau_k))} \tag{9}$$

$$(ii) \kappa(t) = \kappa_0 \exp(-[\kappa_1(t - \tau_k)]^2) \tag{10}$$

$$(iii) \kappa(t) = \kappa_0 + \exp(-\kappa_1(t - \tau_k)) \tag{11}$$

where  $\kappa_0, \kappa_1$  and  $\tau_k$  are parameters that are to be empirically determined. The parameters  $\kappa_0$  and  $\kappa_1$  have the dimension of the inverse of time and  $\tau_k$  has the dimension of time.

To model the cure rate  $\lambda(t)$ , the package will select among these two choices (Eqs. (12) to (13)) that fit the least squares solution best:

$$(i) \lambda(t) = \frac{\lambda_0}{1 + \exp(-\lambda_1(t - \tau_\lambda))} \tag{12}$$

$$(ii) \lambda(t) = \lambda_0 + \exp(-\lambda_1(t - \tau_\lambda)) \tag{13}$$

where  $\lambda_0, \lambda_1$  and  $\tau_\lambda$  are parameters that are to be empirically determined. The parameters  $\lambda_0$  and  $\lambda_1$  have the dimension of the inverse of time and  $\tau_\lambda$  has the dimension of time.

An analysis by Cheynet [48] has shown that the cure rate will increase over time while the mortality rate will decrease over time. This is consistent with the analogy that over time, people's literacy and awareness about the virus will increase, along with better precautions, more health-related resources focused on COVID-19, and control measures implemented by the government. Vaccines and drugs produced would also be more

effective over time with more trials. Hence, it is natural that the cure rate will increase over time and the death rate decrease over time.

### 3.2.2. Parameter estimation

In this paper, the COVID-19 pandemic will be modelled using the fitted parameters and measured (reported) values from the official reports of cumulative number of cases that are publicly available. In this case, the measured values are gathered from John Hopkins University. The daily cumulative number of confirmed (total) cases, recovered cases, and deaths cases were extracted. The protection rate in this model was defined as the vaccination rate, and the infection rate as the basic reproduction number,  $R_0$ . The fitted parameters are first estimated with publicly available data using the formulae given in Table 5.

Table 6 shows the results of each of the parameter that was estimated using the data and formulae from Table 5. The estimated parameters are then fitted into a preliminary fitting, and this is also used to decide the equation for time-dependent recovery rate  $\lambda(t)$  and time-dependant mortality rate  $\kappa(t)$  as stated in Section 3.2.1 to find the best approximation. Next, the ODE system (Eqs. (2) to (8)) is solved using a MATLAB function 'lsqcurvefit' [55] that employs a nonlinear curve-fitting (data-fitting) in the least-squares sense. The optimized parameters  $\{\alpha, \beta, \gamma, \delta, \lambda_0, \lambda(t), \kappa_0, \kappa(t)\}$  are obtained by solving the coefficient  $x$  that satisfies the equation below:

$$\min_x \|F(x, x_{data}) - y_{data}\|_2^2 = \min_x \sum_{i=1}^n (F(x, x_{data}) - y_{data})^2$$

where  $x_{data}$  are the input data that was obtained from the daily cumulative cases, and  $y_{data}$  are the observed output values. The resulting parameters will then be used to simulate the epidemic based on the fitted values.

### 3.3. Framework for the models used

In this section, the process of modelling the death rate, recovery rate, and the number of cases of COVID-19 will be discussed. All computations will be done in MATLAB, using a generalized SEIR model that considers the quarantined state and other preventive measures. The computations will be done using the generalized SEIR package developed by Cheynet [48] that was utilized to carry out the simulation based on available data. The review of the SEIQRDP model was discussed in Section 3.2, hence, this section will emphasize the structural processes of generating the output.

#### 3.3.1. Generalized SEIR model

As discussed in Section 3.2, the generalized model used in this paper considers seven states  $\{S(t), P(t), E(t), I(t), R(t), D(t)\}$  with fitted parameters  $\{\alpha, \beta, \gamma, \delta, \lambda_0, \lambda(t), \kappa_0, \kappa(t)\}$  that are computed

**Table 5**  
The first estimates of the parameters with their descriptions and formulae.

Parameters	Description	Formula
$\alpha$	Protection/Vaccination rate	$\frac{\text{Rolling 7 day average}}{\text{Total population}} \times 100 \text{ people}$
$\beta$	Infection rate/ $R_0$	$\frac{\sum_{i=1}^n R_{0i}}{\text{Number of days, } n}$
$\gamma$	Inverse of average latent (delay) time	$\frac{1}{\text{Average incubation time of COVID - 19}}$
$\delta$	Rate at which infectious people enter in quarantine	$\frac{(\text{Total confirmed cases} - \text{Total death cases} - \text{Total recovered cases})}{\text{Total population, } N} \times 100$
$\lambda_0$	Initial recovery rate	$\frac{\text{Total recovered cases}}{\text{Total population}} \times 100$
$\kappa_0$	Initial mortality rate	$\frac{\text{Total death cases}}{\text{Total population}} \times 100$

**Table 6**  
List of countries with their first estimated parameters.

Country	$\alpha$	$\beta$	$\gamma$	$\delta$	$\lambda$	$\kappa$
India	0.03	1.109	6	0.0122	0.7816	0.0114
Russia	0.05	1.098	6	0.2362	2.5827	0.0580
Brazil	0.10	1.137	6	0.4300	4.4140	0.1199
Japan	0.01	1.067	6	0.0119	0.3235	0.0062
Portugal	0.26	1.084	6	0.6793	7.0511	0.1600
Canada	0.15	1.095	6	0.0800	2.1711	0.0583
Cambodia	0.01	0.475	6	0.0021	0.0029	0
Iceland	0.26	0.927	6	0.0041	1.7600	0.0085
Barbados	1.10	0.915	6	0.2185	0.8376	0.0115
New Zealand	0.01	0.849	6	0.0014	0.0474	0.0005

simultaneously and solved by a nonlinear least-squares function. The ODE system (Eqs. (2) to (8)) is written in a matrix form and solved using the fourth order Runge–Kutta process to find the time evolution of each state  $\{S(t), P(t), E(t), I(t), R(t), D(t)\}$ . For clarity, the matrix form is presented as follows:

$$\frac{dY}{dt} = A \times Y + F$$

where  $Y = [S, E, I, Q, R, D, P]^T$ ,

$$A = \begin{bmatrix} -\alpha & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & \gamma & -\delta & 0 & 0 & 0 & 0 \\ 0 & 0 & \delta & -\kappa(t) - \lambda(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & \kappa(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \text{ and}$$

$$F = S(t) \times I(t) \times \begin{bmatrix} \beta \\ \frac{\beta}{N} \\ \beta \\ \frac{\beta}{N} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

First, data of the cumulative number of confirmed, recovered, and death cases obtained from John Hopkins University (JHU) is imported to the workspace. Then, the country that we want to model is selected. Next, the simulation time period is set (i.e., the start date and the end date of the simulation). The country’s information such as the population of the selected country and the

first estimate parameters obtained from the formulas in Table 5 is then typed and the selected country’s death rate and recovery rate is plotted by running the code provided in the package. After the graph of death rate and recovery rate is obtained from the selected country, it is exported and saved in the JPG format. This process of generating the death rate and recovery rate is illustrated in Fig. 2.

The process of generating the fitted vs. measured number of active, recovered, and death cases is similar to process of generating the death and recovery rates. The only difference here is since the fitted vs. measured (actual) cases were modelled using real data, adjustment had to be made on the time period in order to get the fitted model close to the measured model. For instance, in some countries, the number of active cases were only available after certain dates such that when we input the start date when the active cases data were still unavailable, the result would not be able to model the fitted cases since the exposed, infectious, quarantined, recovered, and deceased cases (E, I, Q, R, and D, respectively) would be zero due to zero active cases during the initial period. As presented in Eq. (3), the states are intercorrelated so that when one of the state’s data is unavailable, it would affect the model as a whole.

The active cases are modelled based on Eq. (14):

$$\text{Active cases} = \text{Confirmed} - \text{Deaths} - \text{Recovered} = \text{Quarantined.} \tag{14}$$

Since there are no available data for the quarantined cases, all active cases are assumed to be quarantined cases, whereby all those who are tested positive for the virus will be immediately quarantined.

The process of obtaining the fitted vs. measured graph is illustrated in Fig. 3.

#### 4. Factors affecting the spread and susceptibility to COVID-19

In this section, the factors affecting the susceptibility to COVID-19, and how the control measures implemented in each country affect the spread of this virus will be reviewed and expounded.

##### 4.1. Age and comorbidity

Age is a significant factor that affects the susceptibility of an individual to disease. For COVID-19, older people were found to be more prone to contracting and suffering a more severe progression of the disease (Jin et al. [24]). According to Dowd et al. [56], the high COVID-19 death count in Italy was related



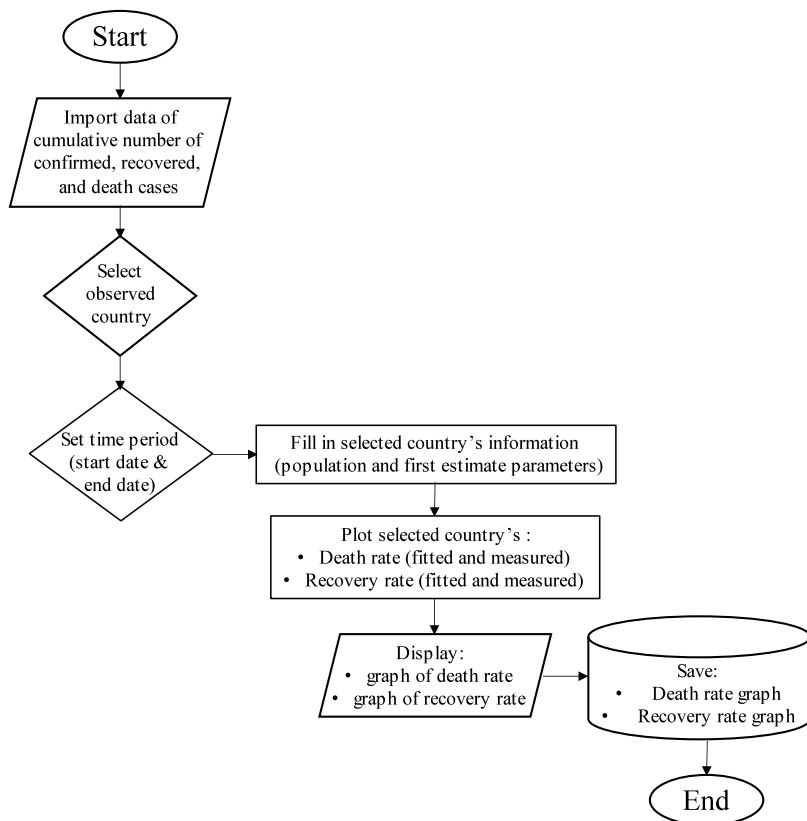


Fig. 2. Flowchart of the process for generating the death rate and the recovery rate.

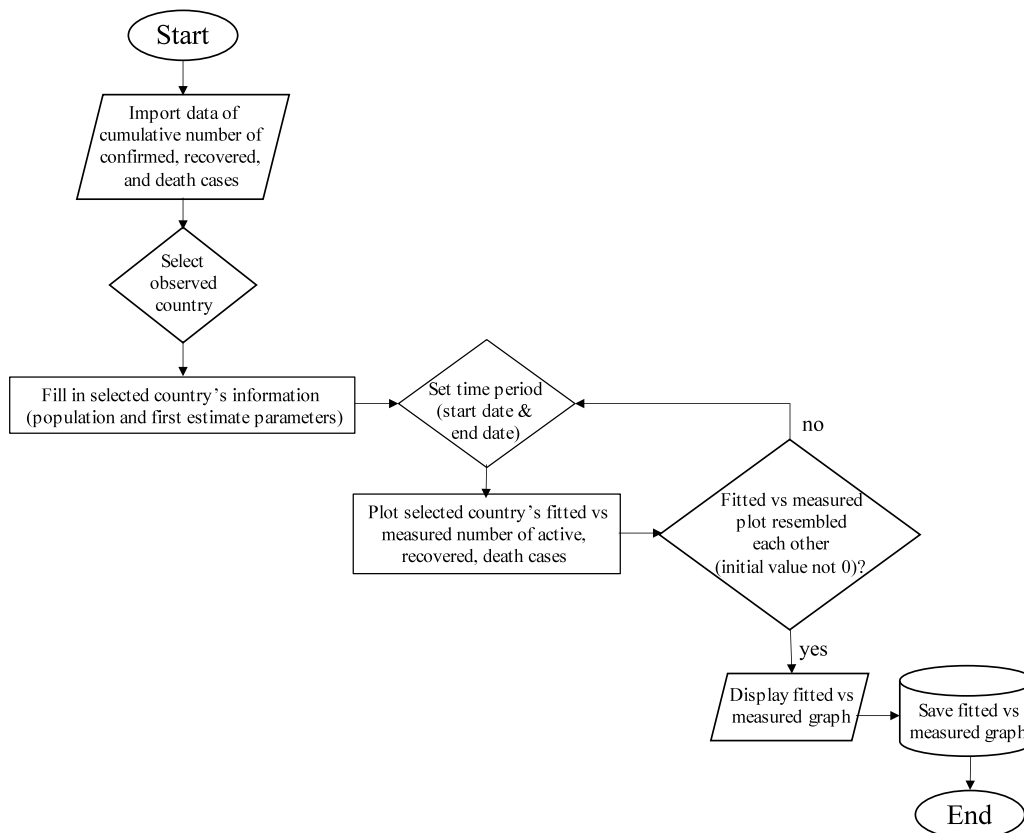


Fig. 3. Flowchart for the process of generating the graphs for the fitted vs. measured number of active, recovered, and death cases.

to the fact that those aged 65 years and above constituted 23.3% of the total population, unlike the lower figure of 14% in South Korea, which led to a mortality forecast of 1.7 times greater for Italy than that of South Korea. Verity et al. [8] reported that the highest case fatality ratio (CFR) in Wuhan falls under the age group of 80 and above, and the lowest CFR falls under the age group of 10 and below. There were also a higher number of reported cases among older age groups in Wuhan, possibly indicating the more severe conditions among the elderly that put them at the top of the priority list for hospitalization. From these observations, it is evident that the case severity and CFR increase considerably with age.

Another important contributing factor to the susceptibility and severity of an individual towards the COVID-19 disease would be the presence of underlying health conditions. A study by Jin et al. [24] indicated a relationship between the chronicity and mortality of COVID-19 patients with older age and comorbidity. Almost two-fifths of the infected patients and more than half of the deceased patients in the study had at least one underlying illness, most of which were linked to hypertension, cardiovascular diseases, and diabetes. The deceased patients were also significantly older with a mean age of 70.3 years, and none of them were paediatric patients. This goes to show that older patients are more prone to succumb to a severe type of COVID-19 as most of them already have at least one underlying disorder. The results in a COVID-19 excess mortality study by Banerjee et al. [23] were also consistent with the theory of the elevation of chances of contracting this disease in the presence of underlying conditions as above 20% of the research population suffered at least one health condition. A study by Sanyaolu et al. [17] concluded that COVID-19 patients aged above 65 years with comorbidities had higher chances of being admitted into the intensive care unit (ICU) and/or have a fatal outcome. Research by Guan et al. [19] seconded this theory as results showed that those with comorbidities suffered severe clinical outcomes. Younger individuals have a stronger immune system and hence are more capable of fighting this disease. Nogueira et al. [20] observed no excess mortality for COVID-19 below the 55-year age group in Portugal. Therefore, it is safe to say that age and comorbidity play an important role in determining the likelihood of an individual being infected by COVID-19, and the level of damage it will cause to that individual.

#### 4.2. Gender

Many studies found that the severity of the disease in male patients tends to be more critical than in female patients [57–60]. Many countries reported similar infection rates in men and women but a higher mortality rate for men compared to women across similar age groups. It seemed that men have a lower resistance towards this disease, and many succumb to it. Jin et al. [24] found that both males and females were equally vulnerable to the COVID-19 disease, but men had elevated chances of a more dire condition during the progression of the disease that may lead to a fatal outcome. In South Korea, death rates were higher among males than females (Shim et al. [57]), and this was even discussed in the World Economic Forum [58]. The higher death rate in men was thought to be related to mast cells, which defend the body from parasitic infections. It was suggested that women were more resistant towards the disease compared to men as their mast cells are capable of instigating a more active immune response, therefore being more competent than men in combating contagious diseases. Women also have a stronger immune response as the X chromosome contains more immune genes, and females have two X chromosomes while males only have one, hence the lack of resistance in men. The elevated risk

of infection in men was thought to be related to the presence of androgens which was categorized as a risk factor for COVID-19. A more subjective factor that may lead to a higher mortality rate in men would be the social behaviours and cultural norms which observe a more frequent habit of smoking and drinking in men, who also tend to delay in seeking medical attention and may wash their hands less.

#### 4.3. Control measures

During this pandemic-stricken time, it is up to the world leaders to devise intricate plans of action to prevent the escalation of this pandemic from getting out of hand. The countries selected for this study have each come up with their action plans to battle this plague.

To measure the strictness of the governmental response, the Blavatnik School of Government from the University of Oxford developed the Oxford COVID-19 Government Response Tracker to compare the worldwide governmental responses to curb this pandemic [53]. This response tracker collects details on countries' governmental responses and categorizes them into separate numerical indicators, which is then used to formulate a figure which informs us of the strictness of the overall response, known as the stringency index. The index used in this study considers restrictions such as the closing of schools, workplaces, and the usage of public transport, the cancellation of public events, restrictions on gatherings and movements between regions and cities, stay-at-home requirements, and international travel controls like screening the arriving passengers or the closing of borders.

The next section will discuss the control measures taken by each country considered in this study, and the effect of implementation of these measures on the rate of spread of this virus. The trend of the daily stringency index and the basic reproduction number  $R_0$  will be compared. The source of the  $R_0$  values is from the John Hopkins CSSE team and was processed by Arroyo-Marioli et al. [61], using the Kalman filter. According to Delamater et al. [62], the basic reproduction number,  $R_0$ , is defined as the contagiousness of infectious agents and its value is affected by various environmental, socio-behavioural, and biological factors. This discussion focuses only on the socio-behavioural factors, and how limiting human contact can affect the transmission rate of the virus. The period available for the  $R_0$  values are different for each country, and the total number of days for which the data is available is stated at the bottom of each graph. A 14-day window is assumed for the government response to influence the  $R_0$ , since it takes between 1–14 days [51] for the symptoms to develop.

### 5. Results, analysis and discussion

In this section, the results of this study are presented and discussed. This section aims to analyse the results obtained using the SEIQRDP model towards COVID-19 cases in 10 countries and present an analysis of the factors affecting the spread and susceptibility of COVID-19 based on current research.

#### 5.1. Results obtained from sentiment analysis

The SEIQRDP model was used to analyse the available data of the cumulative number of COVID-19 cases, including confirmed cases (those infected with COVID-19), recovered cases, and death cases collected by Johns Hopkins University for the COVID-19 epidemic [49]. This model is available as a package in MATLAB and was developed by E. Cheynet [48]. For its parameter optimization, this package used the 'lsqcurvefit' [55] function. To solve the fitted parameters, an estimation of the parameters was first computed from the datasets and the estimated parameters

**Table 7**

The list of countries in this study with their respective regions and COVID-19 cases frequency category (high, medium, low).

Frequency	Continent			
	Asia	Europe	North/South America	Oceania
High cases (> 1,000,000)	India	Russia	Brazil	–
Medium cases (10,000 ≤ X ≤ 1,000,000)	Japan	Portugal	Canada	–
Low cases (< 10,000)	Cambodia	Iceland	Barbados	New Zealand

Remarks: The total number of cases are from 22nd January 2020 to 28th February 2021. Data was retrieved from Johns Hopkins University [49].

**Table 8**

The 10 chosen countries with their respective total number of total COVID-19 cases from 22nd January 2020 to 28th February 2021.

Country	Confirmed	Deaths	Recovered	Population
India	11,112,241	157,157	10,786,452	1,380,004,385
Russia	4,198,400	84,700	3,769,025	145,934,460
Brazil	10,551,259	254,942	9,382,316	212,559,409
Japan	432,090	7889	409,163	126,476,458
Portugal	804,562	16,317	718,977	10,196,707
Canada	871,622	21,990	819,420	37,742,157
Cambodia	820	0	477	16,718,971
Iceland	6049	29	6006	341,250
Barbados	3068	33	2407	287,371
New Zealand	2378	26	2285	4,822,233

Remarks: Data was retrieved from Johns Hopkins University [49].

were inserted into the model, where the estimated parameters will be solved in terms of the least-squares. The model considers 7 different states which were derived from the SEIR model as discussed in Section 3.2.1. The fitting of the parameters was solved by using the nonlinear curve-fitting (data-fitting) in the least-squares sense. The death and recovery rate are expressed in analytical and empirical functions of time. The idea behind this time dependency is that the death and recovery rate would converge towards a constant value as time increases. If the death rate is kept constant, the number of deaths may be overestimated. Births and natural death were not modelled here. Therefore, the total population, including the number of deceased cases, was kept constant. In this study, 10 countries were chosen from different continents and based on the number of COVID-19 cases as shown in Table 7, while Table 8 shows the total number of COVID-19 cases in these 10 countries from 22nd January 2020 to 28th February 2021.

5.1.1. Recovered

The recovery rate for each country based on the measured and fitted parameters is shown in Figs. 4, 5, and 6. The measured and fitted rates are represented by the scattered blue dots and the red lines, respectively. The measured rate was calculated by using the cumulative daily recovered COVID-19 cases from Johns Hopkins University (JHU). The fitted parameters as discussed in Section 3.2.2 were used to approximate the recovery rates using a least-squares method. The recovery rate based on fitted parameters was simulated for 400 days. It was observed that the fitted vs. measured recovery rates closely resembled each other except for Barbados and Cambodia. This pattern could be because of the lower number of confirmed cases in these countries which caused them to have more outliers, i.e., those with extreme cases. Among the chosen countries in this study, countries with a higher number of cases as indicated in Fig. 4 tend to have an increasing pattern of recovery rate as compared to countries with a medium or lower number of cases; countries with a low number of cases as indicated in Fig. 6 tend to produce a linear or constant recovery rate.

5.1.2. Deaths

The death rate for each country based on the measured and fitted parameters are shown in Figs. 7, 8 and 9. The measured and fitted rates are represented by the scattered black dots and the red lines, respectively. The measured rates were simulated using the cumulative daily deaths cases of COVID-19 from JHU. The fitted parameters discussed in Section 3.2.2 were used to approximate the death rates in the least-squares sense. The fitted parameters for the death rate were simulated for 400 days. It was observed that the fitted vs. measured death rates after 100 days closely resembled each other. For India, Russia, Portugal, and Canada, the initial 100 days showed a major spike in the initial death rate, which then smoothens until it reached a constant. This could have been caused by the lack of available information during the initial period when the spread of the virus was still kept at bay, whereas after a certain period, the infectiousness of the virus significantly increased. This in turn led to better prevention measures being implemented to curb the case fatality rate (CFR) through the increase in health care facilities and treatment (Rajgor et al. [63]). Government interventions such as social distancing measures were also found to be vital in curbing the spread of COVID-19 as this eventually led to fewer death cases of COVID-19 (Valenti et al. [64]). The pattern of mortality rates in countries with high, medium, and low cases is shown in Figs. 7, 8, and 9 respectively. Countries with a high number of cases were found to have higher mortality rates compared to countries that recorded medium and low numbers of cases. The mortality rates in countries with low numbers of cases, as shown in Fig. 9 tend to possess constant mortality rates.

5.1.3. Comparison between the fitted and real data

In this study, the available cumulative COVID-19 daily cases from JHU are displayed in Figs. 10, 11 and 12 as the reported number of active, recovered, and death cases, represented by the red, blue, and black lines, respectively. The smooth lines represent the fitted data, whereas the dotted lines represent the measured (reported) data. The fitted parameters were used to estimate the fitted number of active, recovered, and death cases. The simulation was set from 1st May 2020 to 28th February 2021, except for Brazil and Portugal, in which the starting date for the simulations was set to July 2020 and June 2020, respectively. These two countries (Brazil and Portugal) were simulated later since the initial cases before the respective months were close to 0 and caused the parameters computed to be close to 0, thereby causing the fitted results to be less accurate. The simulation enhanced the fitted parameters and produced better results. The active cases in this model were obtained by subtracting the number of deaths and recovered cases from the confirmed cases. As shown in Figs. 10, 11, and 12, the fitted vs. measured graph for the active, recovered, and deceased populations of COVID-19 cases closely resembled each other. All countries have increasing recovery cases and the tendency to reach constant deaths rates. As for the active cases, it tends to peak at least once during the simulation period. In India, the number of active cases peaked around October 2020. In

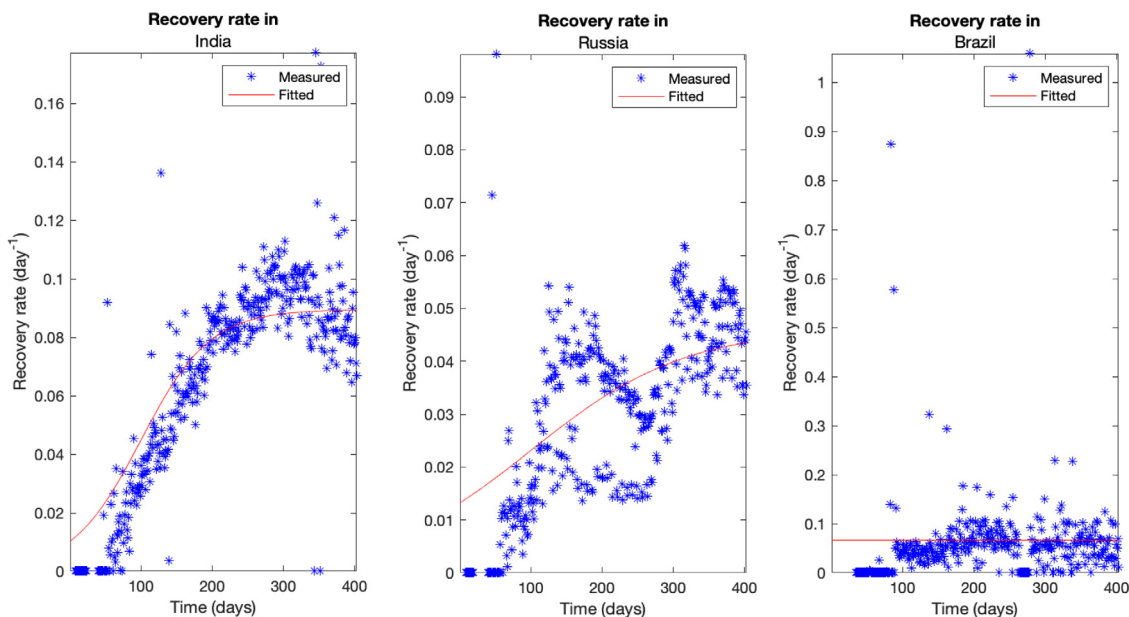


Fig. 4. Recovery rate of countries with high cases. From left to right: recovery rate of countries from Asia, Europe, America.

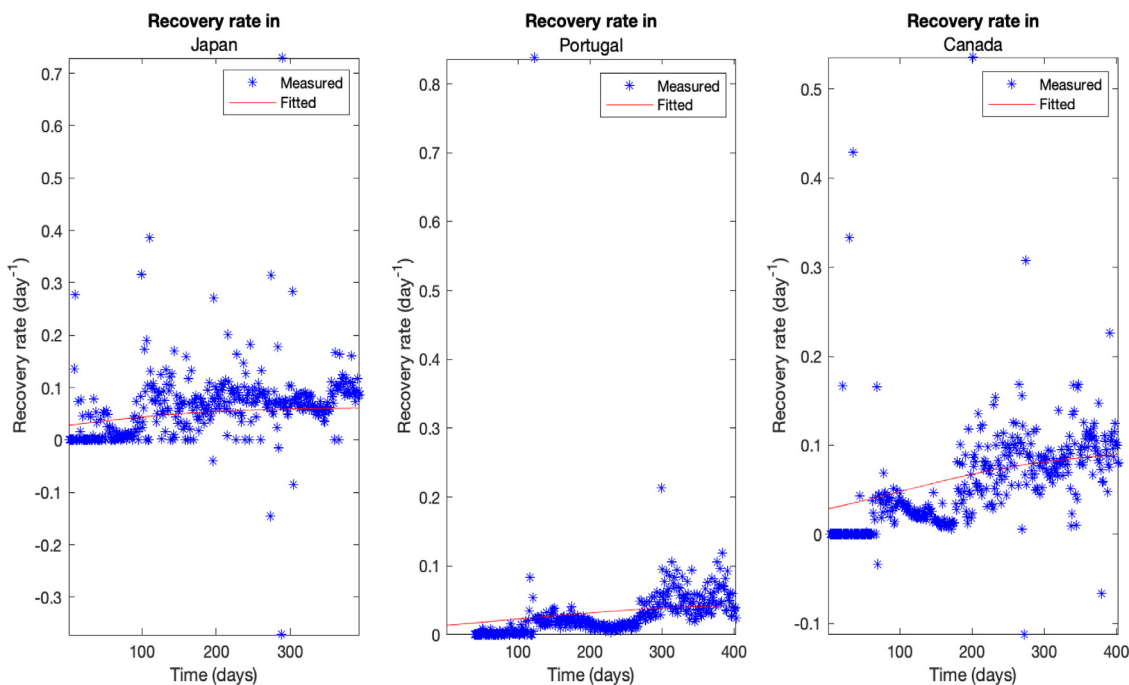


Fig. 5. Recovery rate of countries with medium cases. From left to right: recovery rate of countries from Asia, Europe, America.

Russia, Brazil, and New Zealand, although a significant peak was absent, the number of active cases has the potential to reach its pinnacle in January 2021, early November 2020, and September 2020, respectively. In Japan and Portugal, the number of active cases peaked around late January 2021, whereas in Canada, it happened around January. In Iceland, the number of active cases reached its maximum at the end of November 2020. In Cambodia, the number of active cases had several peaks, however, the highest peak was around February 2020 and might peak again in March 2021. The number of active cases in Barbados seemed to spike significantly from January 2021 and peaked around the end of February 2021.

#### 5.1.4. Country-specific analysis and discussion

The discussions above used a general lens in reviewing the factors considered in this study. The country-specific results that analyse the case fatality rate (CFR) for each factor, and how the control measures implemented in each country influenced the overall spread of the virus will be reviewed in this section. One limitation in this section is that the period of study is not the same for all the countries that are studied.

#### India

Singh, Khullar and Sharma [65] found that within the Republic of India, those aged 50 years and above are more susceptible to the SARS-CoV-2 virus and had a higher chance of fatality. Joe et al. [66] concluded that as of May 20th, 2020, in India,

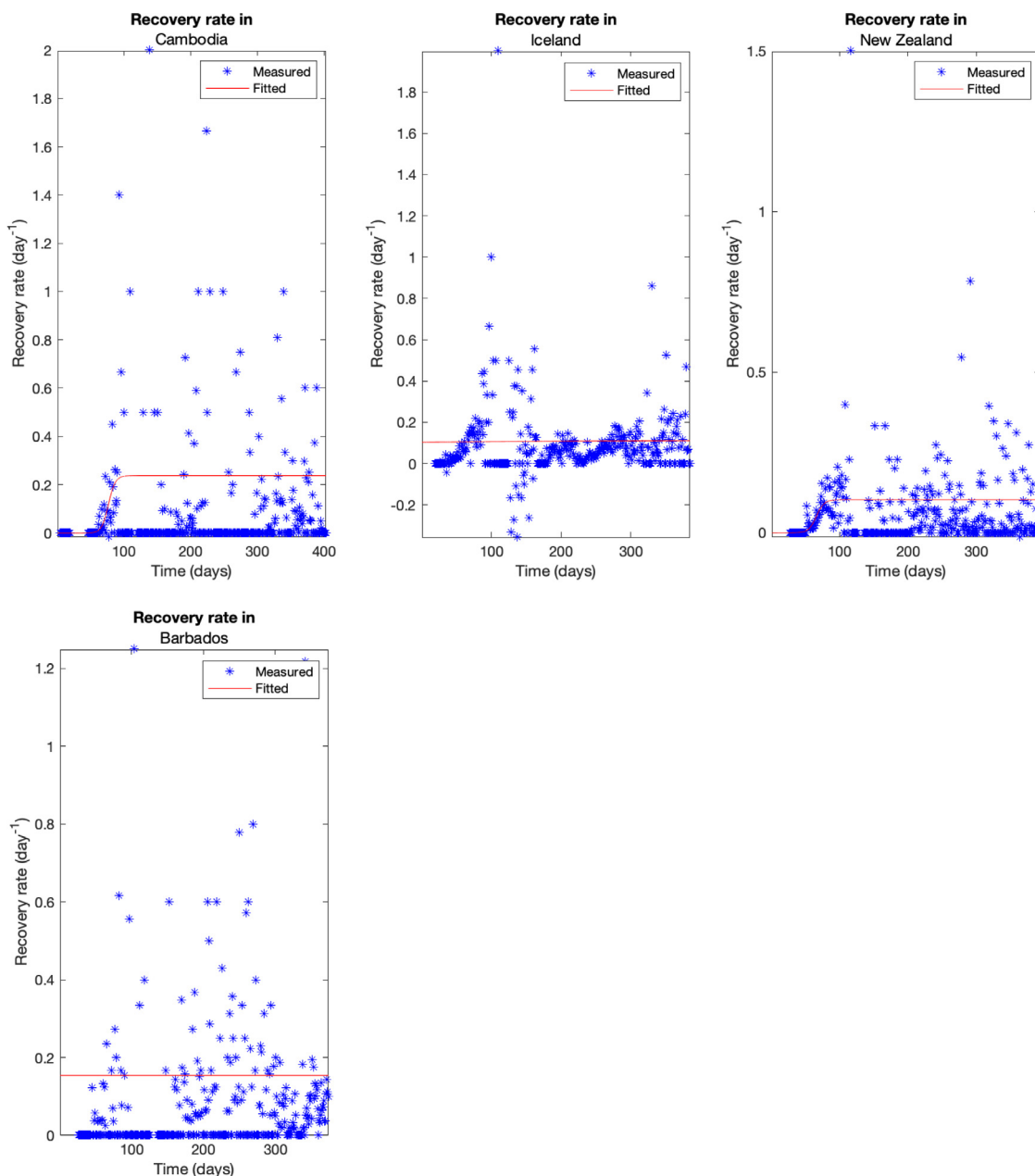


Fig. 6. Recovery rate of countries with low cases. From left to right: recovery rate of countries from Asia, Europe, North/South America, and Oceania.

the elderly had a higher probability of contracting the disease. The highest CFR in both genders falls under the highest age group in the study, 80 years and above. This conclusion can be associated with existing comorbidities like heart-related diseases and diabetes. It was also noted that men had a higher tendency to experience these conditions at an earlier age, therefore making them more vulnerable to the coronavirus. Moreover, this research also discovered that while males experience a more severe progression of the disease when infected, females tend to have a higher CFR. Based on Fig. 13, it is evident that the response by the Government of India was effective in lowering the  $R_0$  of the virus. Both timelines seem to mirror each other starting around April, displaying a negative correlation between the variables. The  $R_0$  starts to decline around mid-April, which is consistent with the expected outcome due to the lockdown imposed in 22 states by the government on the 22nd of March 2020 [67]. The decline drags on until the end of the year. Governmental efforts made throughout the year include extended lockdowns [68], thermal

screening of arriving passengers at 20 airports [69], and the mandatory implementation of wearing facial masks with jail time penalties for any insubordination [70]. One of the early initiatives made by the government was the airport thermal screening in January, before the emergence of any coronavirus cases. However, the  $R_0$  showed a slight increase at the beginning of 2021, possibly due to the phase-by-phase easing in lockdown which began in June 2020 [71]. India began the first phase of vaccination in mid-January 2021 [72], and by the 11th of March, over 20 million citizens have received the first dose of the vaccine [73].

### Russia

In a study by Sharov [74], by the end of April 2020, it was found that 65.6% of the CFR belonged to those aged 65+. A staggering 92.6% of the data analysed had at least one underlying medical condition. The most common were diabetes, obesity, and cardiovascular diseases. Data and studies related to Russia's gender-specific cases are not available, therefore no conclusion

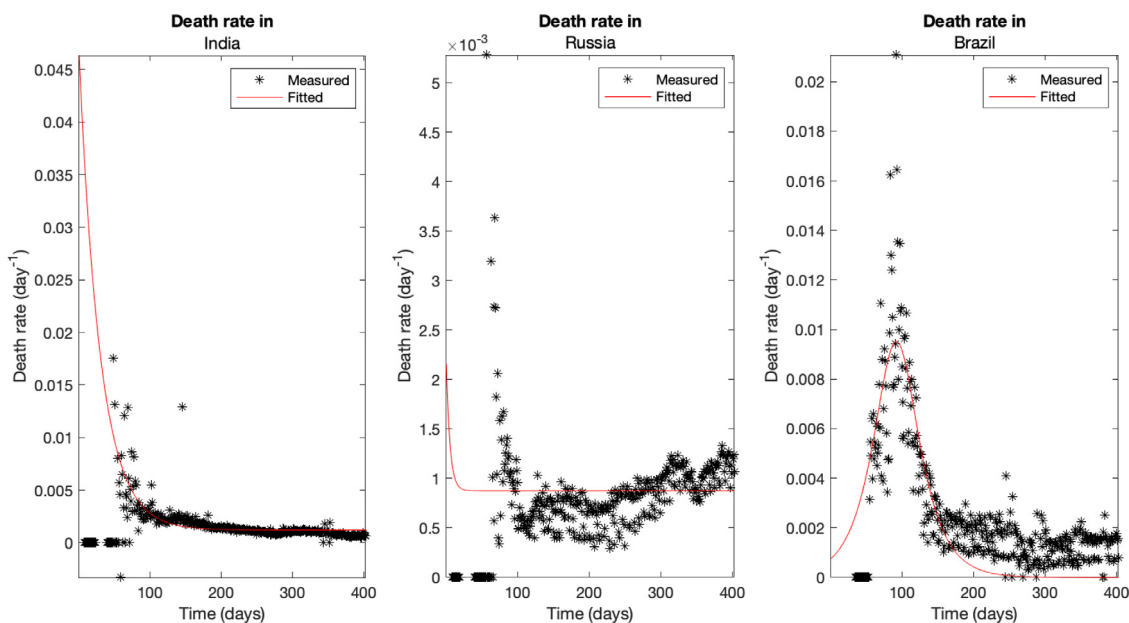


Fig. 7. Death rate of countries with high cases. From left to right: death rate of countries from Asia, Europe, North/South America.

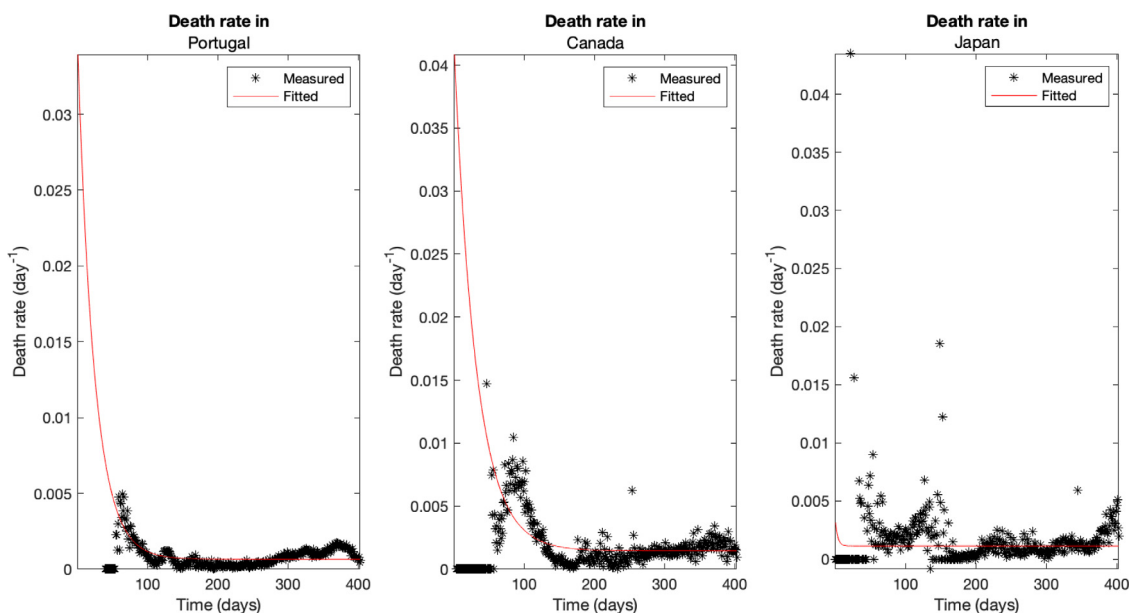


Fig. 8. Death rate of countries with medium cases. From left to right: death rate of countries from Asia, Europe, North/South America.

can be made regarding the gender factor. The stringency index and  $R_0$  in Russia shows a slight negative correlation, suggesting a positive impact of the government response against the virus. The highest point of the  $R_0$  was during the end of March 2020, and it took a steep fall after that, around the same time when international flights were suspended [75], the country's borders closed [76], and the capital, Moscow, put under lockdown [77]. In mid-April, digital permits were issued in the capital for those travelling to work and for private trips to track and limit the citizens' movements [78]. This effort is displayed graphically in Fig. 14 when the first increase in the trend of the stringency index was observed. At the end of September, the  $R_0$  started to rise again, following the decline in the stringency between July and early August. Many restrictions were eased in July, allowing the reopening of various entertainment centres, schools, and

universities, and even eased the ruling on wearing masks [79]. International flight restrictions were also relaxed [80]. Both trends showed little changes towards the end of 2020.

**Brazil**

According to Pachiega et al. [81], until May 20th, 2020, 6.4% of the confirmed COVID-19 cases resulted in the demise of the patients, of which more than half were males. 83% of the total death cases were associated with comorbidities, in which cardiovascular diseases were the most common, with diabetes coming in second. Those aged 60 and above constituted 71.4% of the total deaths in this study. From Fig. 15, it is quite apparent that there is a strong negative correlation between the two variables in question. Both trends reflect each other, and it is safe to say that the  $R_0$  is quite dependent on the overall strictness of the enforcements made by the government pertinent to this pandemic. As the

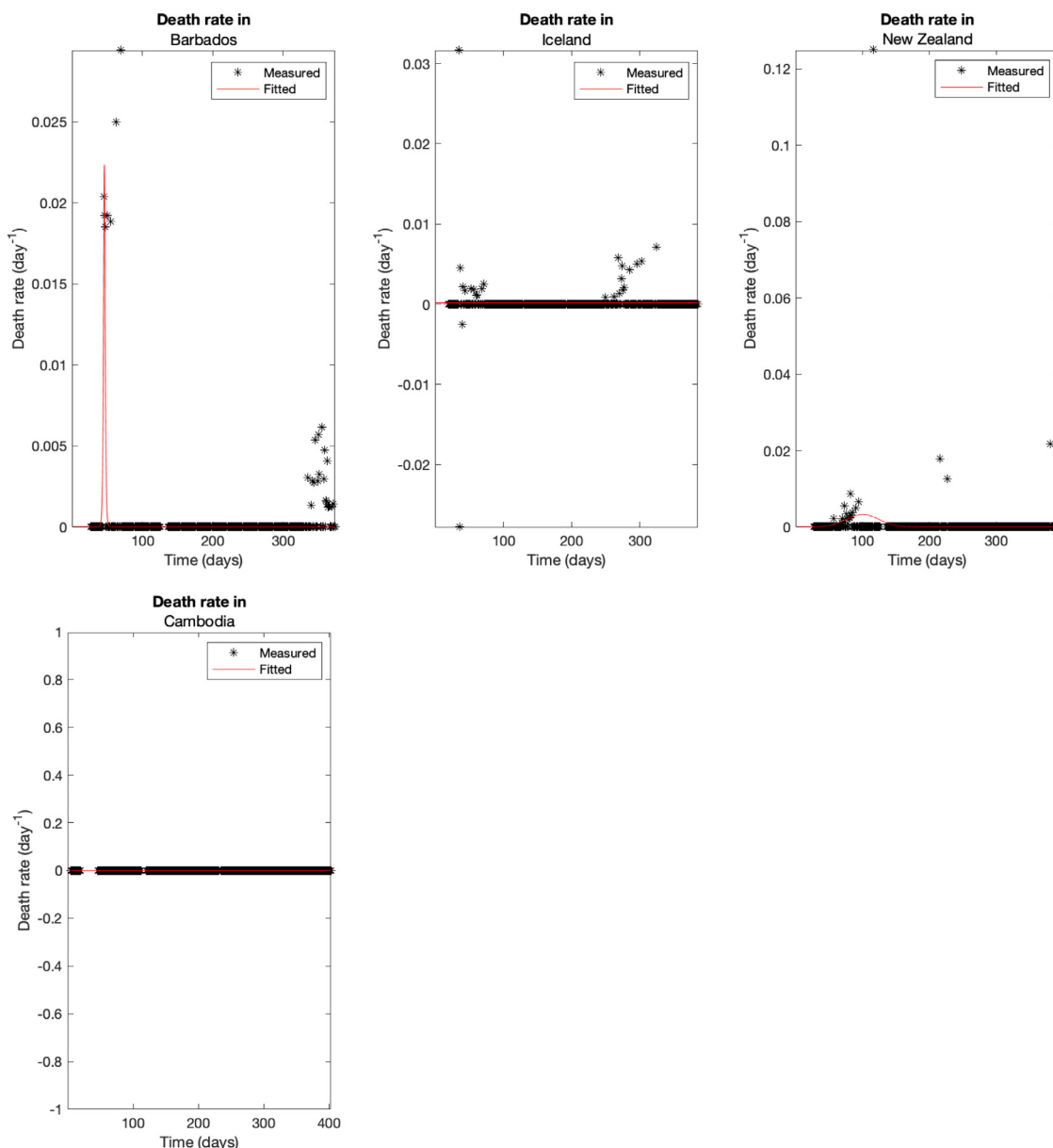


Fig. 9. Death rate of countries with low cases. From left to right death rate of countries from Asia, Europe, North/South America, and Oceania from left to right.

stringency trend begins to rise during mid-March, the  $R_0$  seemed to descend simultaneously. Later, in October, when the stringency index drops briefly, the  $R_0$  trend mirrored this and started to rise again in early November. Some of the measures implemented by the Ministry of Health in Brazil involved the closing of schools, universities, entertainment centres, and all shops except pharmacies and food shops. Religious services, public gatherings, as well as sports and social events were cancelled. However, even with these efforts and the evident reduction in the  $R_0$ , cases have been rising exponentially, especially within the poorer communities and the densely populated areas with tropical climates. It is even harder to break the chain of transmission since many Brazilians within these communities need to work, which voids the option of self-isolation.

### Japan

Kayano & Nishiura [82] found the age-specific CFR for this country to be the highest among those aged 90 and above, resulting in an overwhelming 33.22% of the total CFR for all age groups. There were no deaths for those aged 19 and below. Data

and studies related to Japan's gender-specific cases, as well as its relevance to existing comorbidities, are not available, therefore no conclusion can be made regarding these factors. Based on Fig. 16, the stringency index and the  $R_0$  in Japan show a special trend where slight changes in the stringency index cause a drastic movement in the  $R_0$ . For instance, a minor increase in stringency at the end of February 2020 resulted in a drop in the  $R_0$  at the beginning of March. After that, a large increase in the  $R_0$  due to infected patients returning from overseas resulted in its peak value of 1.7 around mid-April. However, it did not take long for the values to plummet to the minimum in May, which is possibly due to the state of emergency declared on the 7th of April for several prefectures [83]. Six categories of businesses were also requested to close during this period [84]. This trend repeats itself another few times throughout the whole period. One of the main reasons why even a small government implementation can result in such a huge change is due to the heavy compliance of the citizens. Rather than imposing penalties for non-compliance, the Japanese government 'urged' the people to abide by the measures imposed and relied upon their conformance [85]. Other

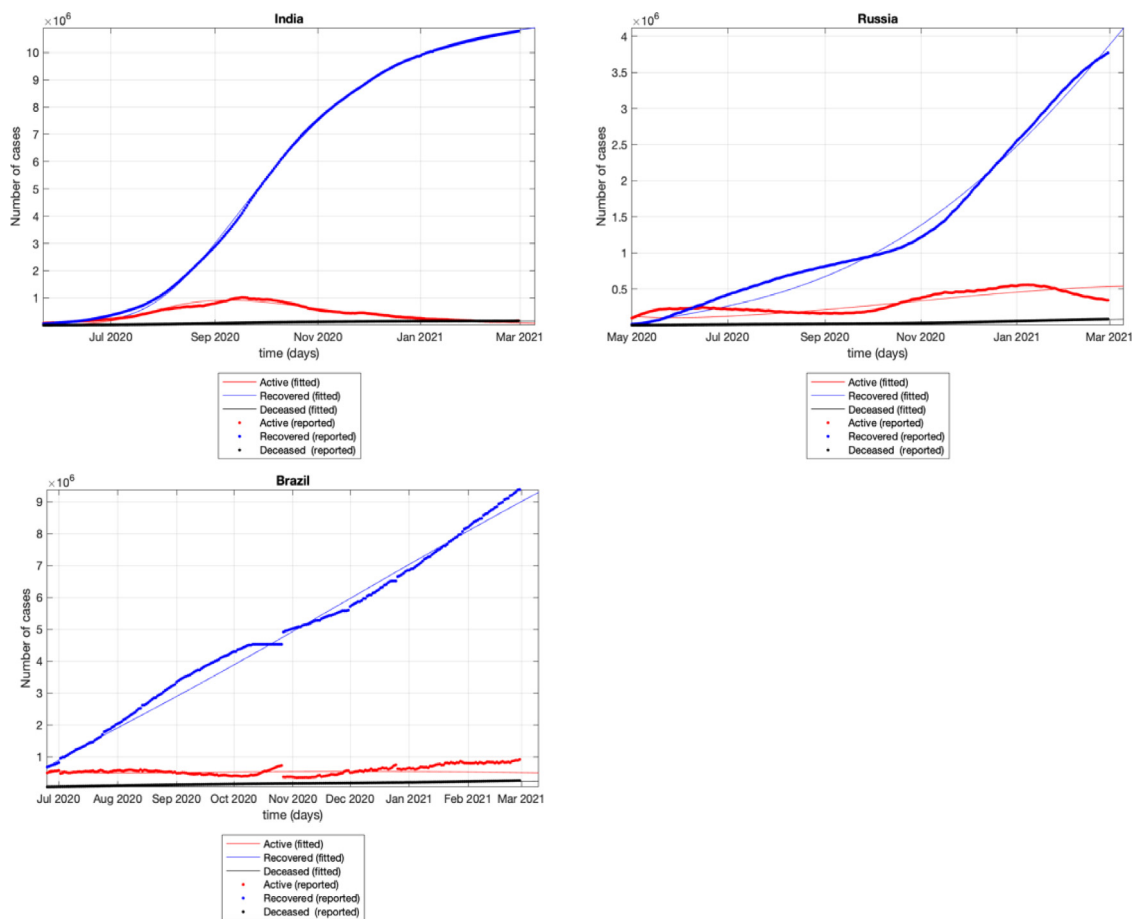


Fig. 10. Number of cases of countries with high cases. From left to right: number of cases of countries from Asia, Europe, America.

governmental initiatives made include the closing of schools [86], entry restrictions at airports [87], and the advice to keep buildings and premises well ventilated [88].

**Portugal**

According to Hoffmann & Wolf [89], as of July 6, 2020, male deaths in Portugal make up 51.12% of the total deaths, and 86.11% of the total deaths were represented by those aged 70 years and above. Ahrenfeldt et al. [59] deduced that the age group with the highest cumulative mortality rate (CMR) was the 80+ years group, and the CMR was higher for the males in all age groups. Analysing all the confirmed cases between 1 January 2020 and 21 April 2020, Nogueira et al. [20] found that males and the age group above 86 years had the highest death rate, whereas, among those who died, the most common present precondition was cardiac diseases and kidney disorders. As shown in Fig. 17, there was a plummet in the  $R_0$  towards the end of March, following a steep rise in the stringency index as the Portuguese government declared a state of emergency [90]. The stringency index remained rather stagnant after that, with an occasional boost. However, the  $R_0$  trend continues to rise, but briefly subsided in July.

At the end of January 2021, the  $R_0$  decreased significantly due to the nationwide lockdown imposed earlier that month after a surge in coronavirus cases. Customers were not allowed to dine-in at eateries, sports facilities were unable to operate, public gatherings, social events and leisure activities were not permitted, and grocery stores had to limit their opening hours [91]. Penalties were also imposed upon those who failed to get tested upon arrival at the airport.

**Canada**

In the same study by Hoffmann & Wolf [51], male deaths constituted 45.69% of the total deaths, indicating a higher death rate among women. Here, the age group with the highest deaths is 70 years and above. Between March and July 2020, it was discovered that the most prevalent condition associated with COVID-19 related deaths were dementia and Alzheimer’s [92]. 42% and 33% of the deceased females and males respectively were categorized as COVID-19 comorbidity-specific deaths. Overall, the  $R_0$  appears to respond to the different levels of stringency.

For instance, in Fig. 18, when the stringency index took a sharp rise in March, the  $R_0$  level took a plunge below 1. This outcome is consistent with the public health emergency declared on the 17th of March 2020 [93]. The US-Canada border was restricted to essential supplies only [94]. Education centres were closed, public gatherings were restricted [95], and non-essential businesses were ordered to close [96]. The surge in the  $R_0$  level in June was attributed to the many parties and gatherings held by the younger generation as a few restrictions were relaxed [97]. By the beginning of 2021, the  $R_0$  started to decrease, possibly due to the first phase of vaccination which began in December 2020.

**Cambodia**

A very thorough search of online sources and literature in this area has found that no studies have been done with Cambodia as a subject. This is probably because Cambodia has a very small number of deaths, as it is one of the least affected countries in the world. In fact, as of the 28th of February 2021, this country has recorded 0 COVID-19 related deaths. Therefore, there are no data available to make any conclusions related to this subtopic.



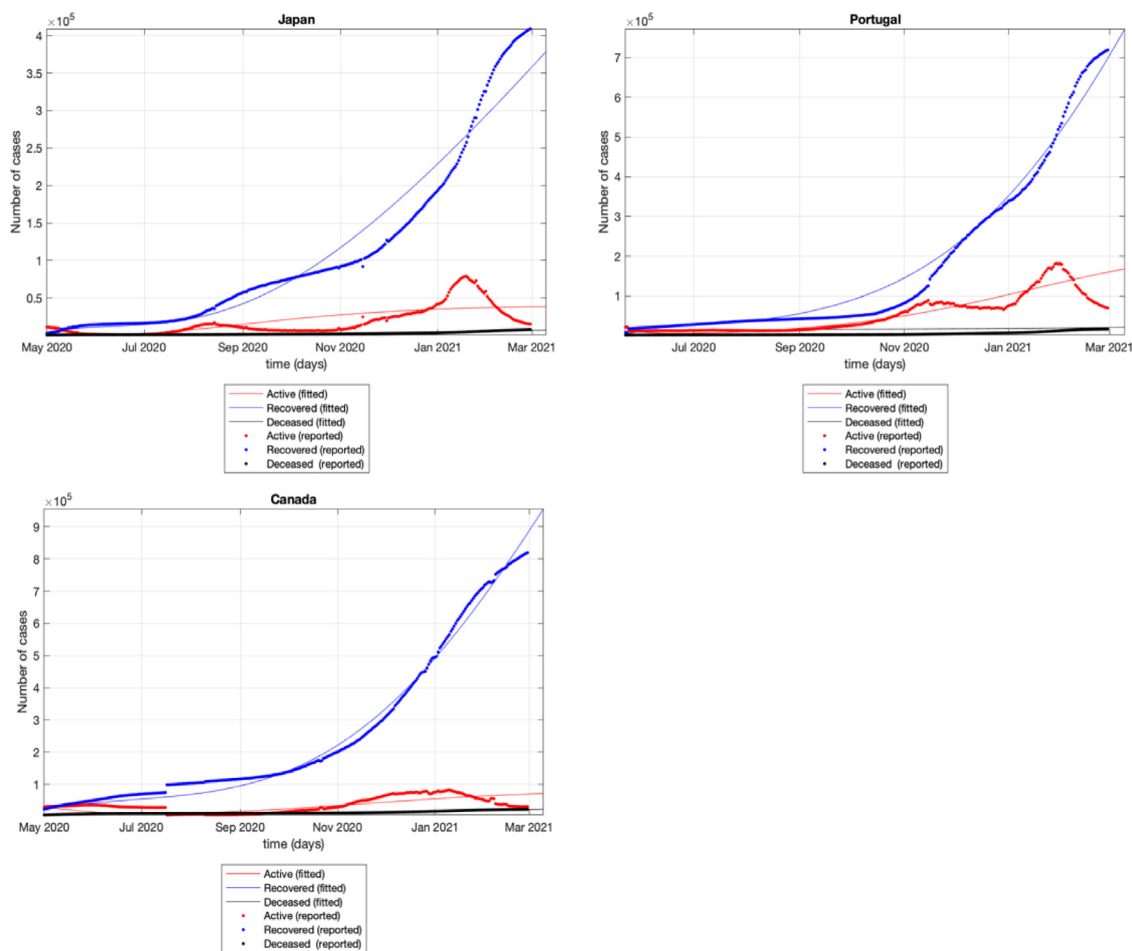


Fig. 11. Number of cases of countries with medium cases. From left to right: number of cases of countries from Asia, Europe, America.

Looking at Fig. 19, it can be clearly seen that the  $R_0$  increased throughout the whole period, with the occasional decline. The  $R_0$  dropped in May after a brief increase in the stringency index in the previous month. Travel restrictions were imposed [98], casinos [99], massage parlours, and health spas were ordered to close [100], and the Khmer New Year was cancelled to avoid a surge in cases [101]. The water festival in Phnom Penh was also cancelled in October to avoid large gatherings [102]. There was a plummet in the  $R_0$  trend in early December 2020, following an increase in stringency towards the end of November.

**Iceland**

The same goes for Iceland, where a thorough search of online sources and literature in this area found no studies with Iceland as a subject due to its very small number of deaths, as it is one of the least affected countries in the world. In fact, as of the 28th of February 2021, this country has recorded 29 COVID-19 related deaths. Therefore, there is insufficient data available to make any conclusions related to this subtopic.

Fig. 20 shows the steep rise in the stringency index in March that triggered a fall in the  $R_0$  level. Universities and schools were closed, alongside the ban on large public gatherings. Not long after reaching its minimum value in May, the  $R_0$  level started to rise again, with occasional declines in mid-August, early October, and January 2021. One of the early initiatives by the Icelandic government includes the screening of passengers at airports for symptoms of COVID-19 [103]. Special shopping hours were reserved for the elderly and those with serious illnesses to prevent their likelihood of contracting the virus [104]. Public facilities like

museums, swimming pools, and libraries were closed, as well as services requiring interactions of less than 2 m [105]. After the sharp rise in cases at the end of September, entertainment centres, bars and gyms were ordered to halt their services again to curb the spread of the virus [106]. The numbers allowed in a public gathering were also cut after the restriction was relaxed for a while. Not long after, the  $R_0$  level, and consequently, the number of confirmed cases started to drop again. These results demonstrated the effectiveness of control measures in slowing the spread of the virus, assuming satisfactory cooperation from the people.

**Barbados**

A thorough search of online sources and literature in this area has found that no studies were conducted with Barbados as a subject. This is probably because Barbados has a very small number of deaths, as it is one of the least affected countries in the world. In fact, as of the 28th of February 2021, this country has only recorded 33 COVID-19 related deaths. Therefore, there is insufficient data available to make any conclusions related to this subtopic. Fig. 21 shows a strong correlation between the two variables. It displays a trend where the  $R_0$  increases as the stringency index decreases and vice versa. Although the data for  $R_0$  was unavailable for the first half of 2020, clear indications that the easing of the control measures had a strong effect on the  $R_0$  in the second half of the year can be seen [107]. Curfews were lifted on the first of July 2020, which very likely prompted the elevation in the  $R_0$  level in the coming months due to the increased human interactions.

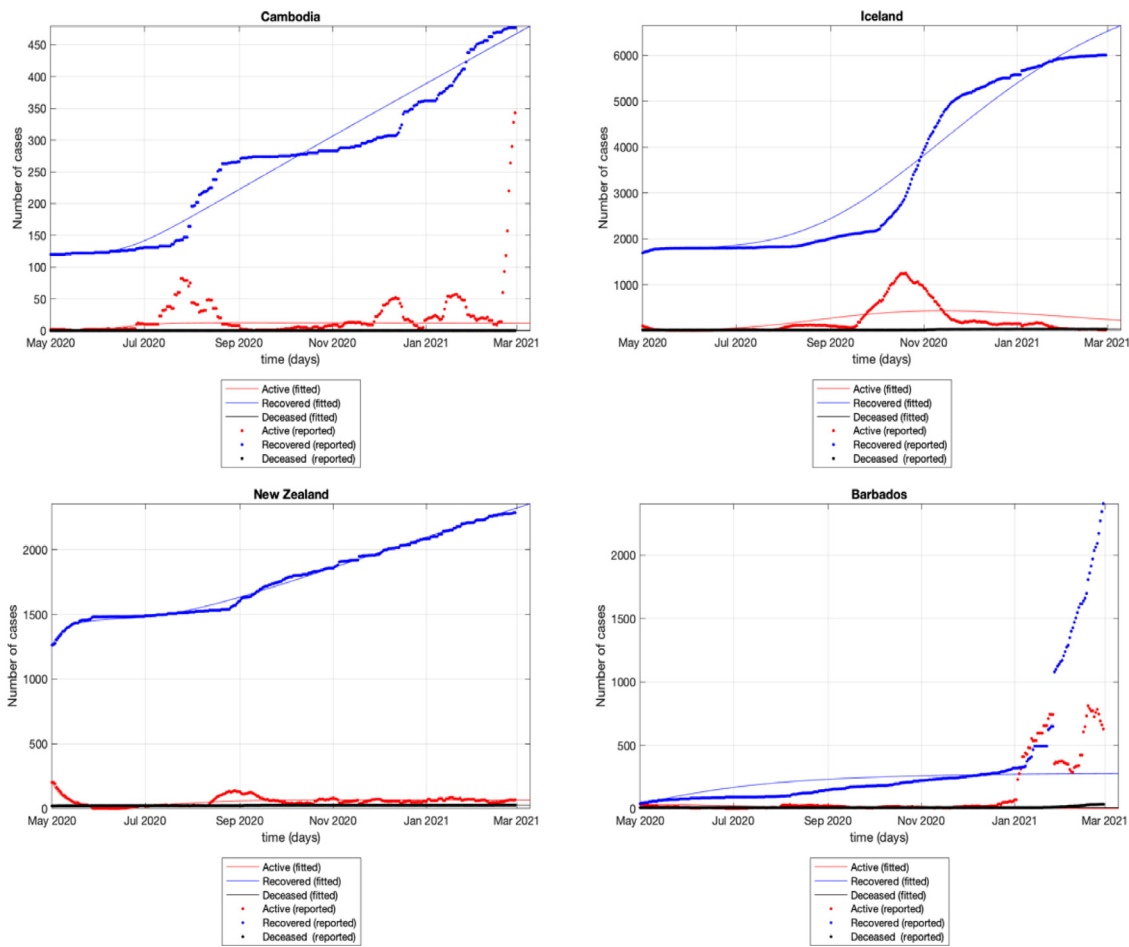


Fig. 12. Number of cases of countries with low cases. From left to right: number of cases of countries from Asia, Europe, America, and Oceania.

Comparison between the trend of Stringency Index and  $R_0$

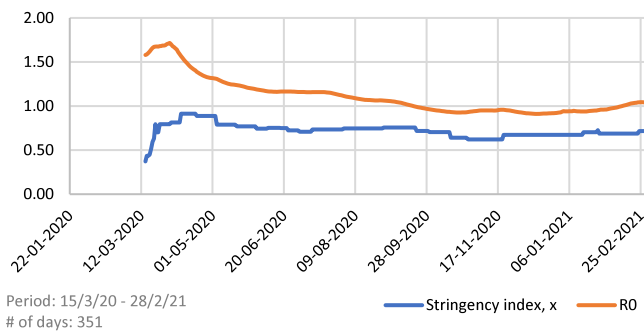


Fig. 13. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in India.

Comparison between the trend of Stringency Index and  $R_0$

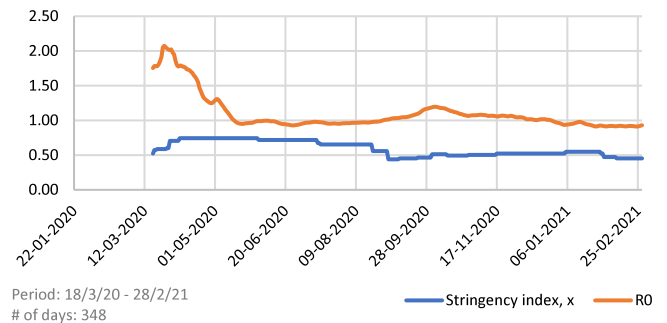


Fig. 14. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Russia.

**New Zealand**

A thorough search of online sources and literature in this area has found no studies discussing the COVID-19 related deaths in New Zealand. This is probably because New Zealand has a very small number of deaths, as it is one of the least affected countries in the world. As of the 28th of February 2021, this country has recorded 26 COVID-19 related deaths. Therefore, there is insufficient data available to make any conclusions related to this subtopic. It is widely known that New Zealand made outstanding achievements in its efforts to eradicate the virus in the country.

This is depicted graphically in Fig. 22. New Zealand’s quick and strict response to the increasing number of cases in the country brought the  $R_0$  level to a steep fall between March and the beginning of June [108]. After that, as restrictions were eased, the  $R_0$  level rose again, and eventually declined after strict measures were imposed again. New Zealand’s strategy in reducing the number of cases was to speed up the swab tests, conduct swift contact tracing, and make sure its citizens adhere to the health restrictions implemented. The rapid upgrade in the capacity to conduct tests allowed the identification of transmission chains

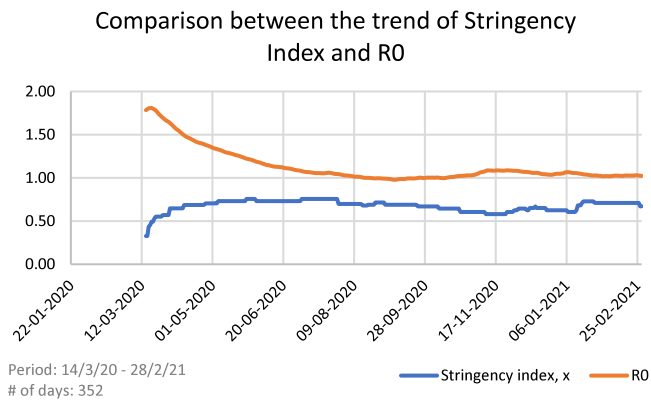


Fig. 15. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Brazil.

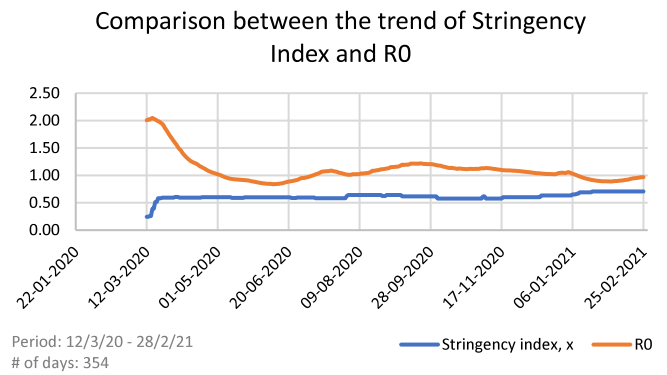


Fig. 18. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Canada.

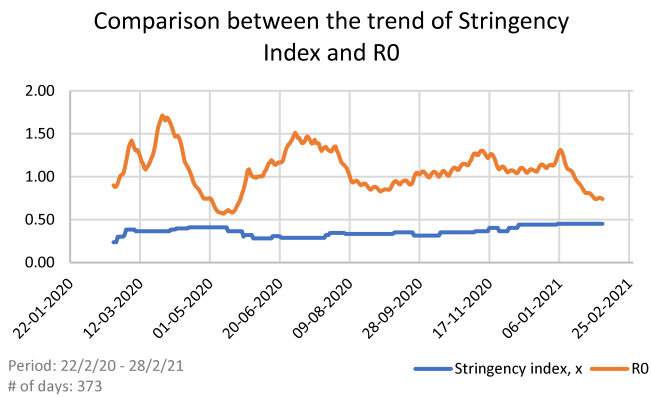


Fig. 16. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Japan.

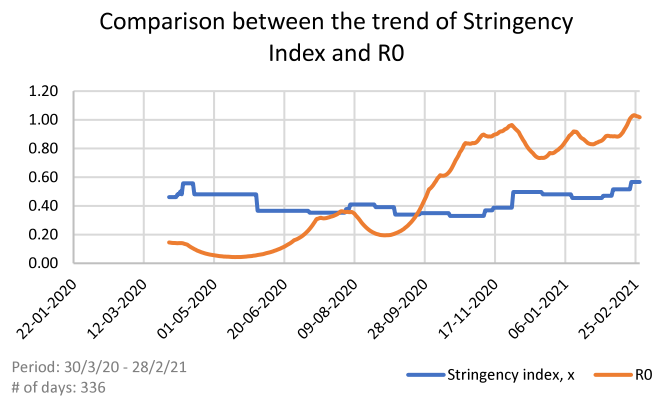


Fig. 19. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Cambodia.

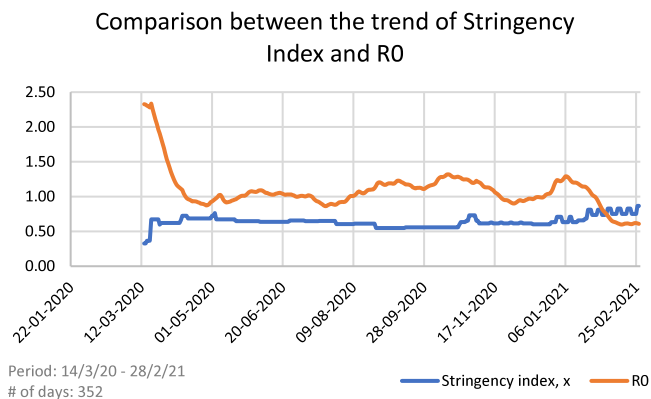


Fig. 17. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Portugal.

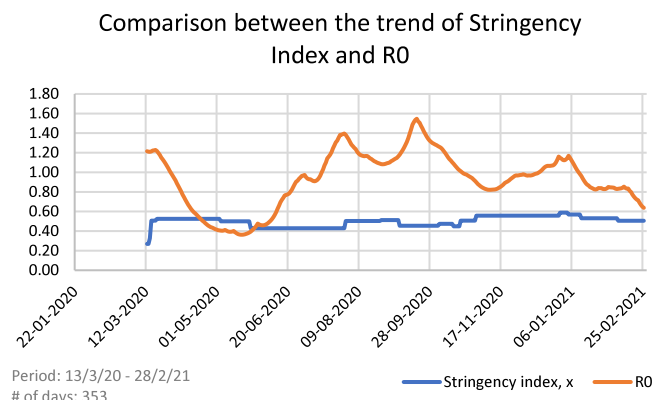


Fig. 20. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Iceland.

before they disappeared into the population, making them untraceable and difficult to eliminate. This allowed those who were in contact with the patient to be aware of their potential illness and to isolate themselves before the onset of symptoms, thereby reducing the risk of transmission to other people [109]. Other important initiatives implemented by the government were to close its borders early and impose a nationwide lockdown with only 102 confirmed cases [110].

Table 9 displays a summary of the discussion of the factors involving age, comorbidity, and gender for the countries in this study. To sum up, based on the countries observed, there is no

conclusion as to whether males or females are more vulnerable to the virus since the results that are available show an equal ratio of CFR between both genders. However, the elderly are certainly inclined towards a higher CFR, most probably due to their weaker immune system since most of them suffer from at least one type of comorbidity. As explained by Biswas et al. [60], diabetes is one of the most common conditions found within the COVID-19 related deaths, weakens their immune system considerably which prevents the body from producing antibodies against the infection. The same goes for cardiovascular diseases, other comorbidities, and severe medical conditions. Hence, it can be concluded that the people that fall within these categories

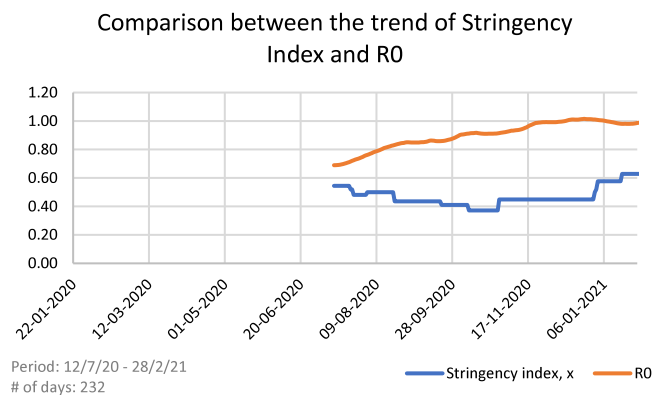


Fig. 21. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in Barbados.

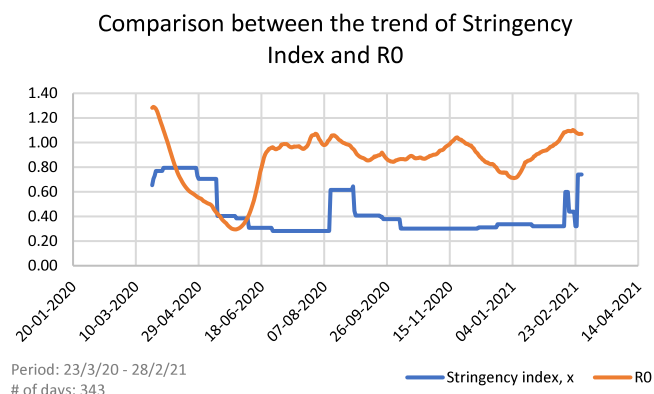


Fig. 22. A comparison between the trend of stringency index and the basic reproductive number,  $R_0$  in New Zealand.

Table 9

A summary of the gender and age group with the highest case fatality ratio (CFR), and the most common underlying health condition among the deceased patients in each country.

Country	Gender with higher CFR (M/F)	Age group with highest CFR	Common underlying health condition among deceased patients
India	F	>50	- Cardiovascular diseases - Diabetes
Russia	-	>65	- Diabetes - Obesity
Brazil	M	>60	- Cardiovascular diseases - Chronic heart diseases - Diabetes
Japan	-	>90	-
Portugal	M	>70	- Cardiac disease - Kidney disorder
Canada	F	>70	- Dementia - Alzheimer's [92]
Cambodia	-	-	-
Iceland	-	-	-
Barbados	-	-	-
New Zealand	-	-	-

(i.e., old age and with underlying health conditions) may have to be more worried as there is a higher risk of them contracting this virus, and they are more likely to experience a more severe case of the disease. It is also evident that the strictness of the control measures imposed by the authorities is extremely influential in restraining the spread of the virus. As observed in New Zealand's case, the time factor played a major role in their success in reducing their cases within three months after the first

case [111]. With just over 100 cases, the country commenced an intense lockdown and started an elimination procedure to free their country of the virus [112]. Their quick response resulted in three COVID-free months from June 2020 [111]. In a study by Koh, Naing & Wong [113], lockdowns, whether full or partial, as well as various physical distancing measures, are most effective when implemented early. By their definition, implementing an early lockdown dictates the need for this action at least 14 days before the 100th case. Every country in this study implemented at least one form of lockdown and urged social distancing among their citizens, and the ones that took early and more stringent initiatives displayed a better outcome than others.

### 5.2. Comparative studies

#### Fractional - Order SEIQRDP model

A study by Bahloul et al. [114] utilized the fractional-order SEIQRDP model to simulate the dynamics of this pandemic. The F-SEIQRDP model is a modified version that is similar to the model in this study. This model adopted the GrnwaldLetnikov scheme based on finite differences in the numerical implementation of the proposed F-SEIQRDP, as opposed to the fourth order-Runge-Kutta process that was used in this study. It is highly capable of illustrating the severity and critical milestones of the spread of this virus using the data collected. It also demonstrates a high accuracy in comparison to the SEIQRDP model. This fact is proven by the higher RMSE values for the SEIQRDP model (RMSE: 381.82) compared to the F-SEIQRDP model (RMSE: 311.14) as depicted in their study (see Table 10).

#### SIR and SEIQR model

A study by Rahimi et al. [115] utilized the SIR and SEIQR versions of this epidemiological model to analyse and predict the outcome of this pandemic. Based on the initial results of this study, before the parameters were optimized, both these models were deemed unsuitable for predicting the results as there was a large gap between the predicted values and the real data.

### Summary/conclusion

Therefore, when we compare these models to the model in this study, it can be concluded that the efficacy of the SEIQRDP model lies somewhere between the efficacy of the F-SEIQRDP and the SIR and SEIQR model. It lacks the ability to illustrate critical milestones in this pandemic, but its prediction considers more parameters compared to the SIR and SEIQR model.

### 5.3. Analysis and discussion of results

Based on Figs. 10, 11, and 12, there are no distinct patterns observed when comparing the number of active, recovered, and death cases by the country's number of cases (countries with high, medium, or low cases). This indicates that there are other factors that contribute more significantly to the changes in the number of active, recovered, and death cases, such as government interventions and control measures, age, gender, and comorbidities. As discussed in Section 4.3, the basic reproduction number  $R_0$  has a negative correlation with the stringency index. Thus, tighter governmental control measures can lead to fewer infections and eventually reduce the number of deaths and active cases while increasing the recovery rate. This can be seen in India, when the  $R_0$  starts to decline around mid-April due to the lockdown imposed by the government in March, during which time the recovery rate was increasing rapidly as shown in Fig. 4, while the death rate starts to decline [70,71]. Both changes took place at around day-90 of the simulation which is around mid-April. This correlation can also be seen in New Zealand, where its quick and strict response in handling the pandemic brought

**Table 10**  
A comparison between the SEIQRDP, F-SEIQRDP, SIR, and SEIQR model.

No.	Model	Parameters	Derivative
1.	SEIQRDP	(i) $\alpha$ ( $\alpha$ ) = protection rate (ii) $\beta$ ( $\beta$ ) = infection rate (iii) $\gamma$ ( $\gamma$ ) = inverse of the average latent (delay) time (iv) $\delta$ ( $\delta$ ) = rate at which infectious people enter quarantine (v) $\lambda(t)$ = time-dependant cure/recovery rate (vi) $\kappa(t)$ = time-dependant mortality rate	Fourth order-Runge-Kutta process
2.	F-SEIQRDP	(i) $\alpha$ : the protection rate. (ii) $\beta$ : the infection rate. (iii) $\gamma$ : the inverse of the average latent time. (iv) $\delta$ : the rate at which infectious people enter in quarantine. (v) $\lambda(t)$ : a time-dependant coefficient used in the description of the cure rate. (vi) $\kappa(t)$ : time-dependant coefficient used in the description of the mortality rate.	GrnwaldLetnikov scheme
3.	SIR	(i) $\beta$ : transmission rate (ii) $\gamma$ : rate of recovery	-
4.	SEIQR	(i) $\alpha$ : protection rate (ii) $\beta$ : infection rate and illustrates the inverse of the average latent time (iii) $\gamma$ : rate of recovery (removal) (iv) $\delta$ : inverse of the average quarantine time (v) $\lambda_0$ and $\lambda_1$ : coefficients used in the time-dependent cure rate (vi) $\kappa_0$ and $\kappa_1$ : coefficients used in the time-dependent mortality rate	-

the  $R_0$  level to a steep fall and eventually made the country COVID-19 free [108]. Studies by Jin et al. [24], Dowd et al. [56], and Shams et al. [116] showed that age is also a significant contributor to the severity of the COVID-19 progression in an individual. In Fig. 5, Japan shows a slightly higher death rate than those in the medium cases category, which is consistent with the fact that 28% of its population comprises of people aged above 65 years old [117], compared to the 22.36% in Portugal [118] and 17.65% in Canada [119]. However, the difference in the death rate is not as significant, which is most likely because of Japan's well-structured health care system, which leads to higher life expectancy [120]. People's behaviour, sociodemographic characteristics, and risk perception of the virus could also fundamentally influence and alter the number of active, recovered, and death cases of an epidemy (Epstein et al. [121]; Van Bavel et al. [122]; Dryhurst et al. [123]). Dryhurst et al. [123] measured the risk perception in 10 countries and found that countries with higher risk perception were associated with lower cases. For instance, at the time of writing, the US had the most COVID-19 cases, and the finding by Dryhurst et al. [123] showed that the US had a low-risk perception. In this study, Russia, one of the countries with high cases can be associated as a country having lower risk perception since most of the entertainment centres, schools, and universities were reopened in June 2020 and some health protocols were eased, including the mandatory implementation

of wearing masks. On the other hand, one unique incident that occurred in India was when its cases plummeted from over a hundred thousand cases a day to just around 10,000 cases per day in a matter of four months [124]. Experts predicted a spike in October, but the opposite happened. Cases started declining in September 2020 and reached an all-time low in January 2021. This radical drop in cases is still a mystery to researchers but a few theories have been discussed [124]. For one, there is a wide awareness of the mandatory ruling on wearing masks, and penalties were imposed on those who did not comply [70]. Secondly, India is a hot country. It was proposed in many studies that the virus was less active in hot and humid conditions, whereas they tend to circulate longer in cold and dry air. Another possible explanation for this sudden plunge in cases might be the stronger immune systems developed by the Indian people due to the numerous existing diseases in the country. Many of them have experienced at least one type of disease, like malaria or dengue, which consequently led to their increased immunity. Millions of citizens experience a deficit of clean food and water, giving them no choice but to survive on what is available, making their immune system more robust over time to other diseases. It was also found that those under 25 make up more than half of India, which might explain the lowered infection and death rates since they have a stronger immune system than older people. Effective vaccination can also curb the proportion of the susceptible population and thus, can significantly reduce the number of COVID-19 cases in the long run through herd immunity [125]. Tables 11 and 12 show the type of vaccine used in each country in this study and its efficacy. Based on Table 12, Pfizer and Moderna are vaccines with the highest efficacy among all vaccines used, followed by Sputnik, V. Both the Pfizer and Moderna vaccines were used in Portugal, Canada, and Iceland. However, based on the recovery rate in Fig. 4 and the number of cases in Fig. 6, there were no distinct patterns from countries that used vaccines with higher efficacy than those with a lower efficacy. Since vaccinations only began at the end of 2020, with most countries beginning in early 2021, it is still too early to tell whether different vaccine efficacy will affect the number of confirmed cases. Moreover, most of the vaccine efficacy is based on preliminary studies and further research is required to be certain of its efficacy in curbing the number of COVID-19 infections. According to Elrashdy, Redwan, and Uversky [126], the SARS-Cov-2 virus has a structure that is optimized for it to transmit easily either by the respiratory route or via the fecal-oral mode. Its quick genetic mutations enable them to develop into multiple variants, allowing a 'viral escape'. This causes the process of developing a vaccine effective enough to eliminate the virus more strenuous as its genetic sequence keeps changing. It also explains its high transmission rate and the difficulty in eradicating this virus even after more than a year and with all the medical and technological advances at our disposal.

### 6. Conclusion

This study implemented the generalized SEIR model that considers the dynamics in COVID-19 transmission such as the quarantine state and vaccination state where there are proportions of populations 'protected' from the virus. This compartmental model was chosen for its flexibility of incorporating the dynamics in a specific epidemy (i.e., incorporating the quarantine states). By utilizing a package with the specified model, the COVID-19 death rate, recovery rate and the number of active cases, the number of deaths, and recovered cases were modelled. The results from the simulation were then observed in order to highlight the key points of the dynamics of the epidemy to analyse the trend of the COVID-19 infections, deaths and recoveries while taking into account as many parameters as possible to ensure a higher accuracy in the resulting model and the analysis of the results.

**Table 11**  
Countries in this study with their respective vaccination period and vaccine used.

Country	Period of Vaccination [50]	Vaccine Used
India	16/1/21–28/2/21	Covaxin, Oxford/AstraZeneca
Russia	16/12/21–28/2/21	Sputnik V, EpiVacCorona
Brazil	17/1/21–28/2/21	Oxford/AstraZeneca, Sinovac
Japan	18/2/21–28/2/21	Pfizer/BioNTech
Portugal	28/12/20–28/2/21	Moderna, Pfizer/BioNTech
Canada	15/12/20–28/2/21	Moderna, Pfizer/BioNTech
Cambodia	10/2/21–28/2/21	Sinopharm/Beijing
Iceland	31/12/20–28/2/21	Moderna, Oxford/AstraZeneca, Pfizer/BioNTech
Barbados	16/2/21–28/2/21	Oxford/AstraZeneca
New Zealand	19/2/21–28/2/21	Pfizer/BioNTech

**Table 12**  
Vaccine used in countries in this study with its respective efficacy.

Vaccine	Efficacy	Source
Pfizer/BioNTech	95%	Polack et al. [127]
Moderna	94.50%	Mahase [128]
Oxford/AstraZeneca	70%	Polack et al. [127] and Voysey et al. [129]
Sinopharm	72.5%	Reuters [130]
Sinovac	50.38%	The Butantan Institute and the Government of Sao Paulo [131]
Sputnik, V	91.60%	Jones & Roy [132]
EpiVacCorona	Undetermined, in early-stage trials	Prüß [133]
Covaxin	81%	BBC [134]

The main findings and contributions of this study are as given below:

- (i) No distinct patterns in the death and recovery rates were found among the countries within the high, medium, or low case categories, suggesting that the similarities in the trend of the pandemic are influenced by the same external factors.
- (ii) Age and gender played a significant role in the severity of the pandemic within a country. It was found that the death rate due to COVID-19 was higher among older people and populations that comprised a larger proportion of older people were at risk of a higher morbidity rate as compared to countries with a lower mean age. CFRs were higher among the older age groups as most of them had at least one underlying health condition.
- (iii) The most common conditions that contributed to the susceptibility to this virus are cardiovascular diseases and diabetes. Patients with underlying health conditions or those who fall into older age groups are at a higher risk of falling prey to this virus due to their weakened immune systems. Consequently, their morbidity rates are also higher than other people.
- (iv) For gender-wise outcomes, most studies reported a higher death rate among males. However, due to the lack of publicly available gender-specific data and the absence of journals discussing the gender-aggregated infection and mortality rates for a few of the countries under observation, this study was unable to conclude how gender distribution affected the number of COVID-19 cases, the death and recovery rates in the countries that were studied.
- (v) Control measures taken by the government have been shown to significantly reduce the basic reproduction number  $R_0$  which led to fewer numbers of cases and eventually increased the recovery rate and lowered the death rate over time.
- (vi) One of the most significant findings was the importance of the time factor in preventing the escalation of a pandemic within the country. This fact, coupled with more

stringent efforts such as imposing national lockdowns, enforcing hardcore contact tracing, and ensuring public compliance are some of the keys to controlling the spread of the virus before it gets out of hand. New Zealand for example, implemented exactly all of these measures diligently, and as a result, they managed to reach zero active cases only 90 days after the first case was recorded.

The limitations encountered in this study are as follows:

- (i) There was a lack of gender-specific data about this pandemic. There were no publicly available data for the number of confirmed positive cases, deaths, and recovered COVID-19 cases stratified by gender. Hence, empirical conclusions regarding the effects of the proportion of gender on the number of cases, recovery rates, and death rates of a certain country were unattainable.
- (ii) The period of study in Section 5.1.4 is not the same for all countries, since the data available for the basic reproduction number,  $R_0$  varied for each country.
- (iii) No journals were discussing the impacts of COVID-19 in countries with low cases. At the time of writing this paper, literature discussing the factors associated with the spread and susceptibility of the virus in all the observed countries within the category of the low cases (Cambodia, Iceland, Barbados, and New Zealand) were unavailable, since these countries were not highly affected by the pandemic and experienced very little COVID-19 deaths.
- (iv) Studies on vaccines and the effects of vaccinations are still in the early stages as most countries only began to implement nationwide vaccinations in early 2021. Thus, the exact outcome of vaccinations on the recovery rates, death rates, and the number of positive cases is still preliminary. Similarly, the impact of achieving herd immunity on the rates of infection, recovery, and deaths due to COVID-19 is still unknown at this point.

Recommendations for future studies on this topic are as follows:

- (i) For further research on this topic, it is recommended to consider more factors that contribute to the model since more comprehensive datasets will be made available to the public in the near future, and these data would be more up to date.
- (ii) Following the publications of more studies in this area, more reliable results will be made available, especially regarding the effects of vaccines and herd immunity on the spread of this pandemic. A thorough study on whether herd immunity is achievable once a certain proportion of people are vaccinated can be done since the effect of a vaccine plays an important role in determining whether a proportion of people are truly insusceptible.

## 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.

## Availability of data and materials

The data that support the findings of this study and the codes that were used in this study are available upon request from the corresponding author.

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## Ethical compliance

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

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