

# Article A Data Driven Analysis and Forecast of COVID-19 Dynamics during the Third Wave Using SIRD Model in Bangladesh

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Abstract: In this study, we developed a compartmental SIRD model to analyze and forecast the transmission dynamics of the COVID-19 pandemic in Bangladesh during the third wave caused by the Indian delta variant. With the help of the nonlinear system of differential equations, this model can analyze the trends and provide reliable predictions regarding how the epidemic would evolve. The basic reproduction number regarding the pandemic has been determined analytically. The parameters used in this model have been estimated by fitting our model to the reported data for the months of May, June, and July 2021 and the goodness of fit of the parameter's value has been found by the respective regression coefficients. Further, we conducted a sensitivity analysis of the basic reproduction number and observed that decreasing the transmission rate is the most significant factor in disease prevention. Our proposed model's appropriateness for the available COVID-19 data in Bangladesh has been demonstrated through numerical simulations. According to the numerical simulation, it is evident that a rise in the transmission rate leads to a significant increase in the infected number of the population. Numerical simulations have also been performed by using our proposed model to forecast the future transmission dynamics for COVID-19 over a longer period of time. Knowledge of these forecasts may help the government in adopting appropriate measures to prepare for unforeseen situations that may arise in Bangladesh as well as to minimize detrimental impacts during the outbreak.

Keywords: COVID-19 modeling; SIRD model; regression coefficient; sensitivity analysis; forecast

#### 1. Introduction

COVID-19 was first identified in the capital of China's Hubei province, Wuhan in December 2019 [1–4]. Bangladesh reported its first confirmed COVID-19 case on 8 March 2020 and continues to report the new cases on a daily basis [5]. In a press conference, the IEDCR confirmed the first three coronavirus cases (IECDR, 2020). Two men and one woman, aged 20 to 35, were confirmed as the first COVID-19 positive cases in Bangladesh. Among them, the two men had returned from Italy, and the woman was a relative of one of the men. On that day in Bangladesh, approximately 111 tests were carried out to diagnose COVID-19 positive cases. On 18 March 2020, the first death of a 70-year-old man as a result of COVID-19 was reported in Bangladesh. To reduce the transmission of the disease, just as in other countries, several measures were implemented in Bangladesh, including a mandatory lockdown, home quarantine, social distancing, and local and international flight restrictions. Bangladesh's educational institutions including schools, colleges, and universities were shut down on 18 March 2020. Following this, all offices were directed to shut down one week later on 26 March 2020, resulting in a national lockdown., Residents were only permitted to leave their houses in emergency situations. All of these measures were taken to reduce the exponential rise of the transmission rate due to COVID-19 in Bangladesh.

Bangladesh has already experienced two deadly waves of COVID-19 prior to the diagnosis of the Indian delta variant cases. The government has tried its utmost to control



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the transmission of the disease throughout the 1st and 2nd waves. Both the transmission rate and the deceased rate significantly decreased across the country. On 8 May 2021, the health authorities of Bangladesh first identified the Indian delta variant of COVID-19 [6]. The variant is considered to be responsible for India's second pandemic wave, which began in February 2021. It eventually caused the third wave in Fiji, the United Kingdom, and South Africa, and the WHO cautioned in July 2021 that a third wave may occur across Europe and Africa [7]. Finally, the third wave of COVID-19 impacted Bangladesh severely, for which the Indian delta variant was responsible. The current wave of COVID-19 has proved to be the deadliest in Bangladesh as the death toll continues to rise and the confirmed cases have eclipsed all prior records. It has been found that the delta variant accounted for 78% of the sampled COVID-19 tests in June 2021 according to recent research conducted by the Institute of Epidemiology, Disease Control and Research (IEDCR), Bangladesh [8]. It has now overrun regions outside of Dhaka, particularly in Khulna's southern division, which borders the Indian state of West Bengal. Even though Bangladesh attempted to close its borders in late April, the policy was not entirely effective as Bangladesh has porous borders with India. Since mid-May, the number of COVID-19 confirmed cases and fatalities continue to rise exponentially and experts have urged the government to reinforce its existing policies to combat the third wave. Despite the Global vaccine supply shortages and stalled deliveries before the third wave, the government has already begun vaccinations across the country to reduce the infection and the fatality rate of COVID-19.

In this study, we analyzed the transmission dynamics of COVID-19 during this third wave that has been caused by the Indian delta variant, and we also forecast the future trends of COVID-19 through the use of the mathematical model. Mathematical models offer the ability to better comprehend the dynamic transmission of infectious diseases as well as forecast their long-term transmission behaviors [9–14]. The probable transmission rate of the disease and the anticipation of the starting and ending time of the epidemic can be determined using mathematical models. Researchers have developed several COVID-19 mathematical models to examine the transmission dynamics in Wuhan, China, and other countries across the world [15–25]. In this study, we proposed a continuous nonlinear compartmental mathematical model containing deterministic ordinary differential equations of susceptible, infected, recovered, and dead (SIRD) individuals to analyze the transmission dynamics of the COVID-19 pandemic and further investigate its future trends in Bangladesh using COVID-19 daily reported data. We undertook the parameter estimation and analyzed the sensitivity of the basic reproduction number relative to the parameters of our proposed model by using the initial values of the variables collected from the daily reported data during the process [26–29]. This model may also be used for other countries to forecast the number of confirmed cases, the number of recovered cases, and the fatalities caused by COVID-19 with sufficient precision. By comparing existing data with analytical results, the proposed model will be able to forecast the stages of COVID-19.

## 2. Data Source

In this study, we have used the data repository maintained by Johns Hopkins University [1] to collect data on the number of cases, of those recovered and of the deceased as our primary source. For our analysis and for the forecast on COVID-19, we have used data from 20 May–23 July 2021. We have also used the DGHS [2], The Humanitarian Data Exchange [3], our world in data [4], and IEDCR [5] as secondary sources for data. The total population chosen for this analysis and for the forecast is 164,689,383 [4]. The data collected from the sources for this study are presented in Table 1.

Date	Cases	Recovered	Deceased	Date	Cases	Recovered	Deceased
20 May	1457	1378	36	22 June	4846	2903	76
21 May	1504	1529	26	23 June	5727	3168	85
22 May	1028	759	38	24 June	6058	3230	81
23 May	1354	899	28	25 June	5869	2776	108
24 May	1441	834	25	26 June	4334	3295	77
25 May	1675	1279	40	27 June	5268	3249	119
26 May	1497	1056	17	28 June	8364	3570	104
27 May	1292	1291	22	29 June	7666	4027	112
28 May	1358	1064	31	30 June	8822	4550	115
29 May	1043	1187	38	01 July	8301	4663	143
30 May	1444	1397	34	02 July	8483	4509	132
31 May	1710	1567	36	03 July	6214	3777	134
01 June	1765	1779	41	04 July	8661	4698	153
02 June	1988	1914	34	05 July	9964	5185	164
03 June	1687	1970	30	06 July	11,525	5433	163
04 June	1887	1723	34	07 July	11,162	5987	201
05 June	1447	1667	43	08 July	11,651	5844	199
06 June	1676	1897	38	09 July	11,324	6038	212
07 June	1970	1918	30	10 July	8772	5755	185
08 June	2322	2062	44	11 July	11,874	6362	230
09 June	2537	2267	36	12 July	13,768	7020	220
10 June	2576	2061	40	13 July	12,198	7646	203
11 June	2454	2286	43	14 July	12,383	8245	210
12 June	1637	2108	39	15 July	12,236	8395	226
13 June	2436	2242	47	16 July	12,148	8536	187
14 June	3050	2564	54	17 July	8489	8820	204
15 June	3319	2243	50	18 July	11,578	8845	225
16 June	3956	2679	60	19 July	13,321	9335	231
17 June	3840	2714	63	20 July	11,579	9997	200
18 June	3883	1955	54	21 July	7614	9704	173
19 June	3057	1725	67	22 July	3697	8566	187
20 June	3641	2509	82	23 July	6364	9006	166
21 June	4636	2827	78				

Table 1. Number of cases, recovered and deceased in Bangladesh from 20 May–23 July 2021.

## 3. Methodology

In order to analyze and predict the behavior and dynamics of infectious diseases, the SIR model is frequently used and is considered to be an effective mathematical tool. The total population is divided into three compartments in this model as follows:

Susceptible class (S)—those who could become infected,

Infected class (I)—those who are infected with the virus at the time,

Recovered class (R)—those who have recovered from the infection.

In this study, we will modify the SIR model, instead using a SIRD model through the inclusion of the compartment of the deceased class (D)—those who have died due to the infection.

#### 3.1. SIRD Model

We will divide the total population into four mutually exclusive compartments of the susceptible population (S), infected population (I), recovered population (R), and deceased population (D) for the model.

In accordance with our model, we made the following assumptions throughout the simulations:

- (i) The total population is closed.
- (ii) The susceptible and infected individuals are homogeneous in the population.
- (iii) The natural death or birth rate is not considered in this model. We only take into account the fatalities associated with COVID-19.
- (iv) The recovered population develops permanent immunity.
- (v) All variables and parameters regarding the model are non-negative.



A diagram of the flow through the compartments is shown in Figure 1 below.

Figure 1. Schematization of the SIRD model.

We assume that the total population (N = 164, 689, 383) [4] is a fixed number over time and is defined by:

$$N(t) = S(t) + I(t) + R(t) + D(t) = constant$$

The SIRD model is governed by the following system of differential equations:

$$\frac{dS}{dt} = -\frac{\beta}{N}SI\tag{1}$$

$$\frac{dI}{dt} = \frac{\beta}{N}SI - (\gamma_R + \gamma_D)I \tag{2}$$

$$\frac{dR}{dt} = \gamma_R I \tag{3}$$

$$\frac{dD}{dt} = \gamma_D I \tag{4}$$

With the initial conditions,  $S(0) = S_0 = N - I_0 - R_0 - D_0$ ,  $I(0) = I_0$ ,  $R(0) = R_0$ ,  $D(0) = D_0$ .

From the above equations, it can be seen that the model depends on the following three parameters: transmission rate ( $\beta$ ), recovery rate ( $\gamma_R$ ), and deceased rate ( $\gamma_D$ ). The transmission rate ( $\beta$ ) represents the growth rate of the number infected with the disease, the recovery rate ( $\gamma_R$ ) represents the growth rate of recovered population and the death rate ( $\gamma_D$ ) depicts the growth rate of the deceased population. We may define the removing rate by  $\gamma = \gamma_R + \gamma_D$  which represents the rate of the population removed from the susceptible population. Detailed descriptions of the variables and parameters are shown in Table 2 below.

Notation	Description
Ν	Total population
S(t)	Susceptible population at time <i>t</i>
I(t)	Infected population at time <i>t</i>
R(t)	Recovered population at time <i>t</i>
D(t)	Deceased population at time <i>t</i>
β	The rate of transmission from susceptible to infectious population
$\gamma_R$	The rate of recovery from infection
$\gamma_D$	The death rate induced by disease

Table 2. Variables and parameters used in the model.

Figure 2 depicts the typical evolution of the variables *S*, *I*, *R*, and *D* over time where the ranges for this model depend on each particular epidemic.



Figure 2. Typical behavior of the SIRD Model over time.

## 3.2. Basic Reproduction Number $(R_0)$

In epidemiology, the basic reproduction number ( $R_0$ ) is one of the most significant factors that indicates the severity of an outbreak. It is defined as the number of contacts from the infected individuals in the susceptible population before the treatment is complete.  $R_0$  is used to determine whether a disease persists in a particular population or not. If  $R_0 < 1$ , each infected person infects less than one person on average, and hence the disease will not be able to spread in a population extensively. If  $R_0 > 1$ , on the other hand, the infection will be able to spread rapidly throughout a population. A greater value of  $R_0$ indicates that it is harder to control the spread of the infection in a population. The SIRD model can be used to calculate the basic reproduction number by dividing Equation 2 by the entire population N.

$$\frac{dI}{dt}\frac{1}{N} = \frac{\beta SI}{N}\frac{1}{N} - \frac{(\gamma_R + \gamma_D)I}{N}$$
$$\frac{di}{dt} = \frac{\beta}{N}Si - (\gamma_R + \gamma_D)i$$

$$R_0 = \frac{\beta}{\gamma_R + \gamma_D} \frac{S}{N} > 1$$

Almost everyone in the population is susceptible at the start of an epidemic, thus we have  $\frac{S(0)}{N} \sim 1$  and hence

$$R_0 = \frac{\beta}{\gamma_R + \gamma_D} \frac{S}{N} = \frac{\beta}{\gamma_R + \gamma_D} \frac{S(0)}{N} = \frac{\beta}{\gamma_R + \gamma_D} = \frac{\beta}{\gamma}$$

where  $\gamma = \gamma_R + \gamma_D$  is defined as the removing rate. If the transmission rate  $\beta$  is higher than the removing rate  $\gamma$ , then  $R_0 > 1$  and the outbreak will be an epidemic. On the other hand, if  $\beta$  is small compared to  $\gamma$  then  $R_0 < 1$  and the outbreak will eventually be eradicated.

## 3.3. Regression Coefficient $(R^2)$

The regression coefficient  $(R^2)$  is a useful tool in compartmental models for predicting future behavior. It is a statistical measure generally used to compare projected values (y) obtained from the SIRD model to real data (x). For each of the four compartments, i.e., susceptible, infected, recovered, and deceased the regression coefficient  $(R^2)$  is calculated separately in the following way to determine the accuracy of the model's fit to the actual data.

$$R^{2} = 1 - \frac{\sum (x - y)^{2}}{\sum (x - \overline{x})^{2}}$$

Here  $\overline{x}$  is defined as the mean of the four compartments regarding the actual data. The value of the regression coefficient ( $R^2$ ) close to unity indicates the better fitness of the functions and the accuracy of the prediction.

#### 3.4. Estimation of Parameters

In general, differential equations are solved by approximating them into separate equations which are solved algebraically to mitigate complexity. Due to stochastic variations in data, this approach may yield substantial uncertainties in some cases. To avoid this phenomenon, we require a more authentic approach to solve the system of differential equations and for fitting the model to the actual data by adopting an effective method. In this study, we solved the set of differential Equations (1)–(4) numerically and fitted the model to the real data of susceptible, infected, recovered, and deceased cases simultaneously, using a nonlinear least squares method. As a specific instance of maximum likelihood, least squares assume that the data are chosen from a normal distribution with the mean determined by the solution to the ODE. The set of differential Equations (1)–(4) is expressed in a typical dynamic model as follows:

$$y' = f(t, y, \Phi), y(t_0) = y_0$$
 (5)

where  $\Phi$  represents the parameters to be determined. We define a least squares objective function as follows for measuring the fit to real data:

$$\xi(\Phi) = \sum_{i=1}^{\infty} (y(i) - \overline{y}(i))^2$$

where y(i) is the fitted data obtained from the solution of (5) and  $\overline{y}(i)$  represents the real data. We have used numerical solver **ode45** in MATLAB to solve the differential equations and applied MATLAB algorithm **lsqcurvefit** to obtain the optimum value of coefficients in the SIRD model, which fits the data to our real data. Regression coefficients ( $R^2$ ) are used

to assess the accuracy of the fitted data obtained from our model. Through the use of the above approach, the values of the estimated parameters and the regression coefficients are provided in Table 3.

Table 3. Estimated model parameters with their regression coefficient.

Parameter			Regression Coefficient			
β	$\gamma_R$	$\gamma_D$	$R^2(S)$	$R^2(I)$	$R^2(R)$	$R^2(D)$
0.2721	0.1988	0.0055	1	0.8135	0.9022	0.9162

#### 4. Results and Discussion

In this section, the numerical findings of the system of Equations (1)–(4) are discussed. By fitting our mathematical model to the real data collected from 20 May–23 July 2021 in Bangladesh as presented in Table 1, we were able to estimate the parameter values of the system of Equations (1)–(4) as well as to conduct numerical simulations to determine which parameters are the most and least sensitive at the estimated parameter values. Finally, we carried out numerical simulations for forecasting the behavior of COVID-19 dynamics for the following 235 days using the values of the estimated parameters.

## 4.1. Interpretation of the Public Data

To analyze the public data presented in Table 1, we used our previously described SIRD model in Section 3. The optimal values for the model parameters that best describe the observed data have been determined through extensive simulations which are presented in Table 3.

The following values from Table 1 are used as the initial values for simulation purposes:

 $S(0) = S_0 = N - (I_0 + R_0 + D_0) = 164,686,515$  $I(0) = I_0 = 1457$  $R(0) = R_0 = 1378$  $D(0) = D_0 = 36$ 

where N is defined as the total population of Bangladesh given by N = 164, 689, 383 [4].

Following the diagnosis of the Delta variant of COVID-19 in Bangladesh, the number of infected and deceased individuals increased rapidly. In this study, we have studied the data during the peak of the delta variant. Figure 3 represents the daily development of the COVID-19 situation of Bangladesh from 20 May–23 July 2021, while Figure 4 represents the cumulative development within this period.

Figure 3a depicts the daily development of individuals infected with COVID-19. From the figure, we can see that the number of infected individuals increases as time passes. Figure 3b represents the number individuals who have recovered from COVID-19. The number of the recovered individuals continues to rise in number as time passes. Figure 3c exhibits the number of deceased individuals due to COVID-19. It depicts that the deceased population as a result of COVID-19 is minimal at first, and then steadily increases over time.



Figure 3. Daily development of the COVID-19. (a) Daily infected, (b) Daily recovered, (c) Daily deceased, (d) Combined (infected, recovered, deceased).



Figure 4. Cont.



**Figure 4.** Cumulative development of COVID-19. (**a**) Cumulative infected, (**b**) Cumulative recovered, (**c**) Cumulative deceased, (**d**) Combined (infected, recovered, deceased).

On the other hand, Figure 4a represents the cumulative development of the infected individuals due to COVID-19. It illustrates that the infected cases in Bangladesh are increasing substantially as the days increase. Figure 4b represents the cumulative development of the recovered individuals from COVID-19. The line shows that the number of recovered individuals grows at an increasing rate with the passing of time. Figure 4c represents the cumulative development of the deceased individuals due to COVID-19. The increasing curve clearly indicates an increasing rate of the deceased population.

In Figures 3 and 4, the number of covid positive cases and the number of deceased cases indicates an increasing trend of community transmission. Despite the high recovery rate, the situation is worsening as the rate of infection and the number of deceased increase as time passes. The situation became more severe as a result of the high rate of infection and the number of deceased after the diagnosis of the delta variant of COVID-19. In response to this, the government of Bangladesh implemented immediate preventive measures within the first few days to mitigate the infection rate by imposing a national lockdown and a mass vaccination program.

The estimated parameters presented in Table 3 determine the value of the basic reproduction number,  $R_0 > 1$  which indicates that the transmission rate is larger than the recovery rate and as a result, the transmission will spread rapidly throughout the population.

#### 4.2. Fitting the SIRD Model to Data

By using the **ode45** solver and **lsqcurvefit** algorithm in MATLAB, we find the fitting of the SIRD model to the actual data presented in Table 1, the outcome for which is shown in Figure 5 below.

Here, Figure 5a–d depicts the fitting of the susceptible, active infected, recovered, and the deceased population respectively. The continuous line represents our model simulation and the circles depict the real reported data presented in Table 1 for all the cases. From this graphical representation, it is observed that the model simulation and the real data align quite well.



**Figure 5.** Fitting model to the actual data. (a) Susceptible fitted, (b) Active infected fitted, (c) Recovered fitted, (d) Deceased fitted.

By using the fitted values represented in Figure 5, all the parameters for our model have been computed with their respective regression coefficients shown in Table 3. Both the regression coefficient and the fitted data represent that our model simulation aligned quite well with the reported data presented in Table 1.

## 4.3. Sensitivity Analysis

The sensitivity analysis demonstrates the relevance of each parameter to the transmission of the disease in epidemiology. As there may be some inaccuracies in the data collection and the estimated values of the parameters, it is often used to assess the stability of the model predictions to the values of the model parameters. It is also used to identify parameters that have a significant impact on the basic reproduction number  $R_0$  and should be addressed through intervention methods. Sensitivity indices enable us to evaluate the relative change in a variable when a parameter changes. The normalized forward sensitivity index of a variable for a parameter is the ratio of the relative change in the variable to the corresponding change in the parameter. When a system's basic reproduction number  $R_0$  is differentiable with respect to the parameter, for example  $\Phi$ , the normalized forward sensitivity index is defined as follows:

$$\Psi_{\Phi}^{R_0} = \frac{\partial R_0}{\partial \Phi} \times \frac{\Phi}{R_0}$$

For each parameter, we may determine the normalized forward sensitivity index of  $R_0$ , which is derived as follows:  $\Psi_{-}^{R_0} = 1 > 0$ 

$$\Psi_{\gamma_R}^{R_0} = -rac{\gamma_R}{\gamma_R + \gamma_D} < 0$$
 $\Psi_{\gamma_D}^{R_0} = -rac{\gamma_D}{\gamma_R + \gamma_D} < 0$ 

It is observed that the sensitivity index  $\Psi_{\beta}^{R_0}$  is positive whereas  $\Psi_{\gamma_R}^{R_0}$  and  $\Psi_{\gamma_D}^{R_0}$  are negative in value. The sensitivity indices will change as the value of the parameters changes since all the sensitivity indices are the functions of the parameters. The sensitivity indices are calculated using the values of the estimated parameters in Table 3. Table 4 presents the normalized sensitivity indices of  $R_0$  with respect to these estimated parameters. The high sensitivity parameters must be estimated carefully, as even a slight change in the parameters might result in significant quantitative changes. From the above equations, we can see that the sensitivity index of  $R_0$  is independent of the parameter  $\beta$  although it depends on the parameters  $\gamma_R$  and  $\gamma_D$ . Table 4 further shows that the value of  $R_0$  is extremely sensitive to the parameters  $\beta$  and  $\gamma_R$ . With the parameter  $\beta$ , it is apparent that the basic reproduction number  $R_0$  reaches its maximum value. More precisely, an increase (or decrease) in  $\beta$  by 100% will increase (or decrease)  $R_0$  by the same value by 100% and an increase (or decrease) in  $\gamma_R$  will increase (or decrease)  $R_0$  by 2.69%.

**Table 4.** Sensitivity indices of  $R_0$ .

Parameter	Sensitivity Index
β	+1
$\gamma_R$	-0.9731
$\gamma_D$	-0.0269

#### 4.4. COVID-19 Forecast for Bangladesh

A forecast of the pandemic is one of the most critical elements for the implementation of effective and efficient tactical preventive measures to reduce infection and fatality. The objective of this study is to explore the dynamics of COVID-19 in Bangladesh over a longer period, utilizing the estimated parameters presented in Table 3. We performed a numerical simulation for the system of differential Equations (1)–(4) using the data in Table 1 for the forecast of COVID-19 for 235 days following 23 July 2021. The simulation anticipates a rise in infection rate, as the disease is rapidly spreading across Bangladesh.

Figure 6 depicts the forecasts of COVID-19 where the red dot represents the real data presented in Table 1 and the blue line represents the predicted value using our model simulation. Figure 6a depicts the forecast of susceptible individuals = to COVID-19. The figure shows that the number of susceptible individuals decreases asymptotically with time. Figure 6b is a prediction of the number of infected individuals due to COVID-19, where the increasing blue line clearly illustrates that the infection rate increases exponentially with time and then decreases after reaching the peak value. Figure 6c represents the anticipated number of recovered individuals from COVID-19. The line shows that the number of recovered individuals from COVID-19. The line shows that the number of recovered individuals grows at an increasing rate with the advancement of time. Figure 6d represents the prediction of the number of deceased individuals due to COVID-19 where the increasing curve clearly illustrates an increasing rate of the deceased population.



**Figure 6.** Model forecasting for COVID-19. (**a**) Forecast of susceptible population, (**b**) Forecast of active infected population, (**c**) Forecast of recovered population, (**d**) Forecast of deceased population.

The predictions derived from our model simulation indicate large variations in the number of cumulative confirmed, recovered, and deceased individuals compared to the real data presented in Table 1. Policymakers are urged to enact preventive measures to reduce the infection rate, such as ensuring the use of face masks, social distancing, quarantine, and disinfecting to flatten the increasing curve according to our model simulation.

As the value of the basic reproduction number,  $R_0 > 1$ , the transmission will spread rapidly across the entire population in Bangladesh. If this current situation remains the same with this existing infection rate, our simulation predicts that the total number of infected and deceased population will be 2,011,284 and the total cases due to COVID-19 would be 74,585,718 after 234 days from 23 July 2021. The discrepancy between the actual reported cumulative value and the predicted value might be ascribed to the proposed system's absence of preventive measures.

Since the infection rate increased drastically after the diagnosis of the delta variant of COVID-19 in Bangladesh, the government immediately took some measures to take the situation under control and decrease the infection. A strict lockdown was imposed immediately in the border district areas to control the transmission rate due to the delta variant. After that, the whole country came under this strict lockdown until 10 August 2021

by increasing the deadline several times. After the lockdown, the government has initiated a mass vaccination program for the people of Bangladesh and made the minimum age limit for vaccination to 18 years to mitigate the transmission rate. The program is still running across the whole country and we are hopeful that the transmission rate will decrease as the immune system is growing high through vaccination.

#### 4.5. Study Limitations

The study has limitations. First, the values of the parameters defining the system are determined by applying field data to COVID-19. Estimating the parameters is a difficult task due to the absence of a significant part of the infectious cycle. The most important limitation is the use of **ode45** and the optimization method **lsqcurvefit** to find the optimum parameters. **lsqcurvefit** is an optimization strategy that can obtain both positive and negative optimum parameters, but the required parameter values are non-negative. In this case, we have to simulate the system using different initial values of parameters until we get positive optimum parameter values.

## 5. Conclusions

In this study, we developed a SIRD compartmental model to analyze the present situation of COVID-19 disease transmission and for forecasting its future developments in Bangladesh. We used the initial value of the variables from the real data in Table 1 and applied curve fitting to obtain the value of the parameters used in the model. The goodness of fit for the parameters has been determined by the regression coefficient. Our findings demonstrate that our proposed model fits well with the reported data collected from 20 May-23 July 2021 in Bangladesh, which has been presented in Table 1. According to the sensitivity analysis, the transmission rate  $\beta$  is the most sensitive parameter. The epidemiological consequence is that increasing this parameter may worsen the situation of the disease in the population. The value of the basic reproduction number  $R_0 > 1$ shows that the transmission of the disease is growing rapidly and that COVID-19 cannot be eradicated from the entire population over a short period of time. Numerical simulations are conducted to validate our model analysis and the model was fitted to the real data for forecasting the future trends of COVID-19. As our prediction shows that the transmission and the deceased rate is increasing day by day, necessary preventive measures should be taken immediately to reduce the transmission and deceased rate by policymakers. Though the government has already imposed strict lockdown measures across the whole country several times during this period, social awareness should be increased among the people to reduce the transmission rate. We acknowledge and appreciate the initiative of the mass vaccination program after 10 August 2021 that has been taken by the government and lowering the age limit for vaccination to 18 years of age. It will take time to vaccinate the entire through the vaccination program, until then wearing face masks should be made mandatory to prevent the transmission rate. Furthermore, the healthcare facilities in Bangladesh are insufficient to treat a large number of COVID-19 positive patients. The capacity of healthcare institutions should be enhanced to assist in reducing the transmission of COVID-19.

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