A New Proposed Model for Covid-19

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Elham Salah Soliman; Dr. Mervat Mahdy Ramadan and Dr. Mohamed Goda Khalil

Abstract

During the broadcast of COVID-19 (Coronavirus) across the world, many mathematicians made several mathematical models, to understand the forecast and behavior of this epidemic's spread accurately. Nevertheless, due to the lack of much information about it, the application of many models has become difficult and sometimes impossible, unlike the simple SIR model. In this study we proposed a new SIRD model for COVID-19. SIRD model is fitted to real data of COVID-19 patients in Egypt using R program, the sample consists of all patients in the susceptible state, infectious state, removed state, and the death state. The purpose of this study is to give a prediction of the epidemic peak and sizes in our country. The results of this study are an indicator for the widespread of COVID-19 in Egypt.

Key words: Mathematical model; COVID-19 pandemic; SIR model; SIR model; SIR model; SIRD model.

1. Introduction

The use of mathematical models in public health such as SIR models play an essential role in many aspects, for example: rapid visualization of epidemiological information, monitoring, prediction and estimating the spread of disease, and helping in decision-making on pandemic prevention and control (Layati et al, 2021).

As stated by the World Health Organization (WHO) report worldwide, as of March 7*th, 2022* since the outbreak of COVID-19 was reported in December 2019, there have been 448 million confirmed positive states of COVID-19, including 6.01 million deaths and over 93.3 million who have recovered. In Africa, as of August 8*th, 2021*, 7,075,119 confirmed positive states have been reported with a total of over 3.27 million deaths (Mayabi et al, 2022).

2. Mathematical Model & Materials

The topic was formalized by Kermack and McKendrick in 1927, who wrote down the first accurate mathematical models for disease transmission in a format that is still used today. The SIR model represents the spread of infectious diseases from which recovered individuals get immunity from re-infection (Black, 2010).

Mitra (2020) studied the epidemic patterns of Covid-19 in India during the period 30 Jan to 10 July 2020 from a mathematical modeling perspective using SIR model with an aim to forecast the precise description of the disease. Marques et.al (2022) proposed a discretized SIR compartmental model as a driving dynamics of disease dissemination through a spatially distributed multipopulational. Olu et.al (2023) used the compartmental model in this study to analyze COVID-19 cumulative and active cases in Nigeria during the year 2020. Sahran & Tee (2023) identified in this study the trend of the COVID-19 outbreak before and after the vaccination campaign by using the Susceptible-Exposed-Infectious-Recovered (SEIR) and Susceptible-Exposed-Infectious-Recovered-Vaccinated (SEIRV) models. Ahmed et.al (2023) analyzed the COVID-19 SIR model and characterized its positivity and boundness properties. Choi et.al (2023) The primary aim of this research is to estimate the number of COVID-19 cases through the analysis of SARS-CoV-2 derived from wastewater samples. Pathak et.al. (2024) proposed a model using a simple SIR model for analysis of the spread and control of COVID-19 pandemic in India after the subsequent lockdown by considering the approach of partial measures. Vanderpas et.al (2024) The trajectory of COVID-19 epidemic waves in the general population of Belgium was analyzed by defining quantitative criteria for epidemic waves from March 2020 to early 2023. The SIR compartmental model was applied to the first epidemic wave.

In this study we proposed a new SIRD model for COVID-19 to improve the SIR model for predicting the numbers of deaths of COVID-19 patients during the prevalence of pandemic in Egypt and to estimate the parameters of the proposed SIRD model. SIRD model is applied to a real data to investigate the dynamics of COVID-19 in Egypt.

The following figure shows the states of the proposed SIRD model and the possible transmissions between them.

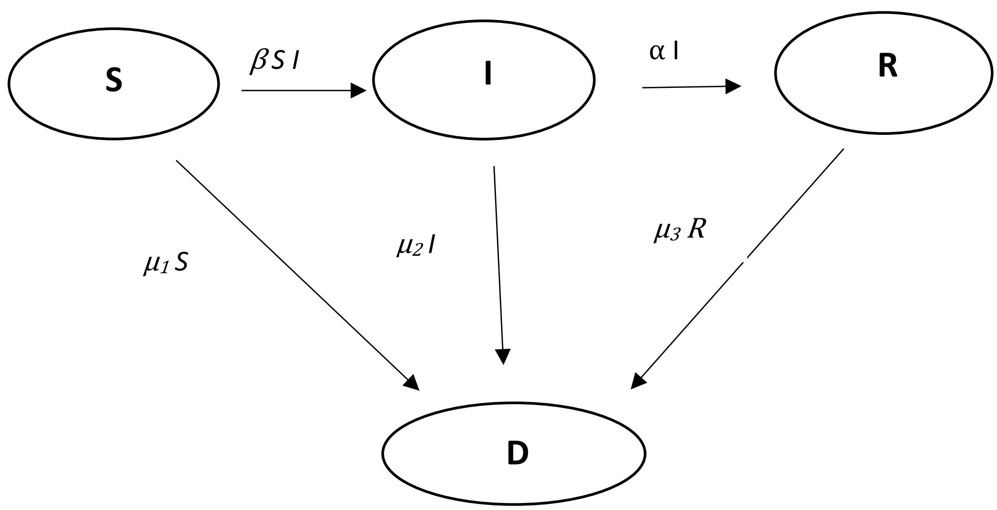

Figure (1): The proposed *SIRD* model

The Proposed SIRD Model

The proposed SIRD model is a system of ordinary differential equations which is defined as follows:

$$\frac{dS}{dt} = -\beta SI$$

$$\frac{dI}{dt} = \beta SI - \alpha I$$

$$\frac{dR}{dt} = \alpha I$$

$$\frac{dD}{dt} = \mu_1 S + \mu_2 I + \mu_3 R$$

with initial conditions $S(0) = S_0 > 0$, $I(0) = I_0 > 0$, $R(0) = R_0$, $D(0) = 0$, and the total population $N = S+R+I+D$. The transmission rate is β, the recovery rate is α and the death rate is μ.

If the values of parameters are not known, some simple observations about the solutions to the proposed SIRD system can be made that hold for each or a big set of possible parameter values.

a) Suppose $N(t) = S(t) + I(t) + R(t) + D(t)$ denotes the total population. Thus, by adding the equations of *SIRD* model it turns out that,

$$\frac{dN}{dt} = 0\,,$$

Thus, the total population $N(t) = N_0 = S_0 + I_0 + R_0$ remains constant.

b) From the equation $\frac{dS}{dt} = -\beta SI$ shows that $\frac{dS}{dt} \leq 0$.
So that, $S(t)$ is always decreasing. Especially $S(t) \leq S_0$.

c) Rewrite the equation $\frac{dI}{dt} = \beta SI - \alpha I$ as follow:

$$\frac{dI}{dt} = (\beta S - \alpha)\, I.$$

Then, the following two cases occur:

1. If $S_0 < \frac{\alpha}{\beta}$, then $\frac{dI}{dt}|_{t=0} < 0$. Since $S(t) \leq S_0 \leq \frac{\alpha}{\beta}$, and $I'(t) < 0$ for all $t \geq 0$, and thus $I(t)$ strictly decreases. As a conclusion, no epidemics can occur in this case.

2. If $S_0 > \frac{\alpha}{\beta}$, then $S(t) > \frac{\alpha}{\beta}$ for $t \in \left[0, \bar{t}\right)$ for some $\bar{t} > 0 > 0$. This implies $I'(t) > 0$ and thus $I(t)$ strictly increases for $t \in [0, \bar{t})$. As a conclusion, an epidemic happens.

The main assumptions of the proposed *SIRD* model are:

- The population remains constant over time, who make up the population move from susceptible to infected.

- The population leaves the infected state recovering from the disease, and those who manage to do so acquire immunity and so can no longer be infected again.
- The death state is added in the proposed SIRD model.
- The population is closed, so, no one from the outside enters the population, and no one leaves the population except the death states. The influx of new susceptible is zero, and so are the removal rates from all states.
- Individuals become infected regardless of age, sex, social status.
- Constant rates (for example: transmission, removal rates)
- The latent period for the disease is ignored.
- Well-mixed population (Allen,2010; Allen,2017; Hethcote, 2000; Brauer et al, 2008; Martcheva, 2015; Li, 2018).

The Proposed SIRD as a Markov Chain

Ching & Ng (2006) defined the transitions probabilities as follows:

The probability P_{ij} represents transition probabilities from an illness state i at to another illness state j.

$$P_{ij} = P\left(X_n = j \mid X_{n-1} = i\right) \qquad i, j = 0,1,2,.... \quad n \geq 0 \text{ .}$$

The transitions probability matrix is defined as follows:

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & p_{14} \\ p_{21} & p_{22} & p_{23} & p_{24} \\ p_{31} & p_{32} & p_{33} & p_{34} \\ p_{41} & p_{42} & p_{43} & p_{44} \end{bmatrix}$$

P is (4×4) square transition probability matrix. The elements of these matrix p_{ij} represent that the patient will be in state j (the future), given it is in state i (the present).

For all i,j in the transition probability matrix there are two conditions:

1. $P_{i,j} \geq 0$,

2. $\sum_{j \in N} P_{i,j} = 1$.

Every row in the probability matrix P shows a vector of transition probabilities where the sum of elements in every row is one. The value of off-diagonal elements of the probability matrix shows the probability of movement between classes and the value of the diagonal matrix shows the probability of a class remaining in year (t + 1) in the same class as in year t (Shabani & Shahnazi, 2020).

According to the data, the state space for the Markov chain consists of four elements defined as follows:

$$C = \{S, I, R, D\}$$

As regards the *SIR* model, the model supposes the time is discrete, the variable t takes values in {0, 1, 2, . . .,}, so the random variables which define the various states of the Markov chain are discrete. In the SIR model, the elements of the population are classified into three states: Susceptible (S), Infected (I), and Recovered (R).

The transitions probability matrix of the proposed SIRD is defined as follows:

$$P = \begin{bmatrix} -\beta SI - \mu_1 S & \beta SI & 0 & \mu_1 S \\ 0 & \beta SI - \alpha I - \mu_2 I & -\alpha I & \mu_2 I \\ 0 & 0 & \alpha I - \mu_3 R & \mu_3 R \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0.2 & 0.6 & 0 & 0.2 \\ 0 & 0.2 & 0.3 & 0.5 \\ 0 & 0 & 0.6 & 0.4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

From the transitions probability matrix it is noticed that $p_{11} = -\beta SI - \mu_1 S$ which means that the probability of being in the susceptible state = 0.2 , $p_{12} = \beta SI$ the probability of transmission from susceptible state to infected state = 0.6 , $p_{14} = \mu_1 S$ the probability of transmission from susceptible state to death state = 0.2 , $p_{22} = \beta SI - \alpha I - \mu_2 I$ the probability of being in the infected state = 0.2, $p_{23} = -\alpha I$ the probability of transmission from infected state to removable state = 0.3 , $p_{24} = \mu_2 I$ the probability of transmission from infected state to death state = 0.5 , $p_{33} = \alpha I - \mu_3 R$ the probability of being in the removable state = 0.6 , $p_{34} = \mu_3 R$ the probability of transmission from removable state to death state = 0.4 and finally p_{44} = 1the probability of being in the death state the absorbing state.

3. Data Description

The total sample of patients consists of 500 COVID-19 patients in the period of the prevalence of the COVID-19 pandemic especially in the first year of its prevalence in 2020 in Egypt. They represent a random sample, and the data of COVID-19 patients is regarded as states of SIRD model. SIRD patients transmit from state to another state in a stochastic manner. Using the R program, the data are supplied to R as a series of states, grouped by patients.

4. Results

The sample size was divided into five groups as follows: 100, 200, 300, 400 and 500.

The first group:

The first group consists of 100 COVID-19 patients and their results are as follows:

Table(1): Results of the first group n = 100

time	S	I	R	D
0	99	1	0	0
1	98.54037	1.343295	0.11634	10.58723
2	97.92695	1.800597	0.272451	21.38685
3	97.11185	2.406738	0.481412	32.46884
4	96.03497	3.204846	0.760188	43.92414
5	94.62297	4.24654	1.130492	55.86932
6	92.78984	5.590592	1.61957	68.4511
7	90.44028	7.298968	2.260757	81.84963
8	87.47759	9.428977	3.093434	96.27894
9	83.81744	12.02059	4.161974	111.9823
10	79.4075	15.07933	5.513178	129.2195
11	74.25044	18.55766	7.191897	148.2454
12	68.42381	22.34123	9.234961	169.2789
13	62.08761	26.24808	11.66431	192.4674
14	55.47201	30.04698	14.481	217.8549

The results of the first group show the risk of the COVID-19 pandemic where there are increases in the number of deaths by the time from 0 on the first day until reaching 218 cases at the end of 15 days.

The following table shows the summary of the SIRD model of the first group:

Table (2): Summary of the SIRD model of n = 100

	S	I	R	D
Min.	1.964897	0.043174	0	0
1st Qu.	1.998341	0.431673	55.76113	572.6826
Median	2.363016	2.96055	93.37945	1212.301
Mean	17.47412	9.707089	72.8188	1144.967
3rd Qu.	10.64055	15.07933	97.56999	1723.782
Max.	99	40.54584	97.99193	2220.531
N	100	100	100	100
sd	30.05438	12.72971	34.76767	679.8512

It is noticed from the table of n= 100 that the data does not belong to the normal distribution and the standard deviation is increased espicially for removed states and death states which refer to Extremely dangerous of COVID- 19.

The following table shows the Maximum likelihood estimations for the first group:

Table(3): Maximum likelihood estimations for n = 100

Parameter	Estimate	SE
Beta	-13.7892	7.01289
Gamma	-9.5689	6.02598
Sigma 1	6.7823	4.28941
Sigma 2	5.68921	3.02698
Sigma 3	7.2587	4.69861

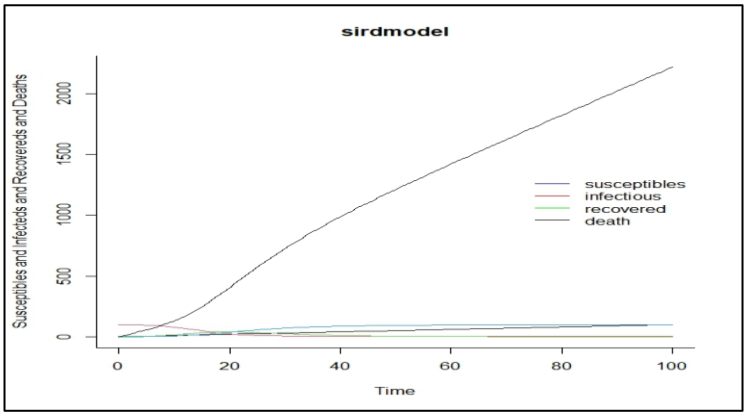

Figure (2): SIRD model at n=100

Figure (2) shows SIRD model when the sample size is equal to 100 of the COVID -19 patients and it is obvious that the number of deaths increases through time from 0 until reaching to 2221 at the end of 100 day which shows the severity of COVID-19.

The second group:

The second group consists of 200 COVID-19 patients and their results are as follows:

Table (4): Results of the second group n = 200

time	S	I	R	D
1	199	1.00+00	0	0
2	197.854	2.00+00	0.144391	20.72834
3	195.5872	3.98+00	0.432459	42.19589
4	191.1849	7.81+00	1.001594	65.1101
5	182.9296	1.50e+01	2.105087	90.77696
6	168.4177	2.74e+01	4.171442	121.4122
7	145.5733	4.66e+01	7.815629	160.2165
8	115.1443	7.12e+01	13.67797	210.5823
9	82.3886	9.56e+01	22.04649	274.1907
10	54.09202	1.13e+02	32.56551	349.5016
11	33.68946	1.22e+02	44.40299	432.5303
12	20.6112	1.23e+02	56.68673	519.0028
13	12.70738	1.19e+02	68.77805	605.7362
14	8.014126	1.12e+02	80.30251	690.8182
15	5.208055	1.04e+02	91.07752	773.2689

The results of the second group show the risk of the COVID-19 pandemic where there are increases in the number of deaths by the time from 0 on the first day until reaching 773 cases at the end of 15 days.

The following table shows the summary of the SIRD model of the second group:

Table (5):Summary of the SIRD model of n = 200

	S	I	R	D
Min.	0.066936	1.07e-06	0	0
1st Qu.	0.066936	1.53e-04	196.7965	2624.328
Median	0.066994	2.19e-02	199.9111	4626.445
Mean	8.191285	1.00e+01	181.8099	4557.791
3rd Qu.	0.075884	2.56e+00	199.9329	6616.199
Max.	199	1.23e+02	199.9331	8605.866
N	200	200	200	200
sd	35.29945	2.56E+01	47.2945	2423.292

It is noticed from the table that the data does not belong to the normal distribution and the standard deviation is increased espcially for removed states and death states which refer to Extremely dangerous of COVID- 19.

The following table shows the Maximum likelihood estimations for the second group:

Table (6): Maximum likelihood estimations of n = 200

Parameter	Estimate	SE
Beta	-11.7892	6.58320
Gamma	-8.96321	5.58961
Sigma 1	6.02631	3.45221
Sigma 2	5.00045	2.00554
Sigma 3	7.00111	3.96621

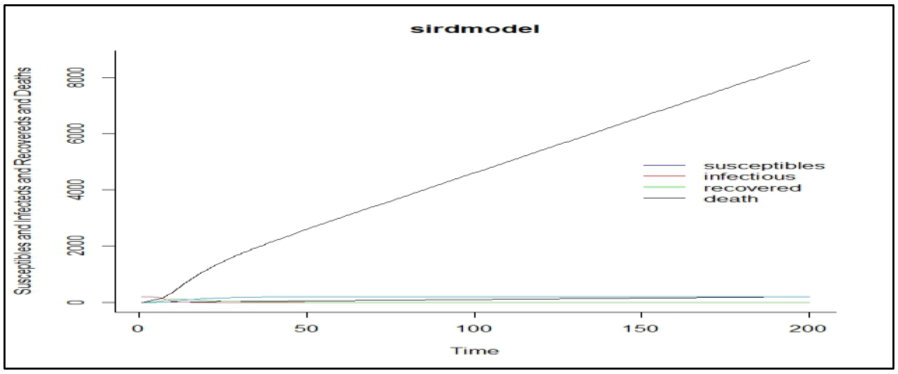

Figure (3): SIRD model at n=200

Figure (3) shows the SIRD model when the sample size equals 200 of the COVID-19 patients and it is obvious that the number of deaths increase through time from 0 until reach to 8606 at the end of 200 days which shows the severity of COVID-19.

The third group:

The third group consists of 300 COVID-19 patients and their results are as follows:

Table (7): Results of the third group n = 300

time	S	I	R	D
1	2.99e+02	1.00e+00	0	0
2	2.97e+02	2.98e+00	0.181516	30.91503
3	2.91e+02	8.75e+00	0.718516	63.64031
4	2.73e+02	2.46e+01	2.260371	101.4855
5	2.32e+02	6.17e+01	6.350485	152.3358
6	1.61e+02	1.23e+02	15.47148	228.9799
7	8.67e+01	1.82e+02	30.95546	338.6717
8	3.91e+01	2.10e+02	50.85548	472.2393
9	1.67e+01	2.11e+02	72.07315	614.4734
10	7.34e+00	2.00e+02	92.69005	755.8055
11	3.40e+00	1.85e+02	111.9368	892.2836
12	1.68e+00	1.69e+02	129.6042	1022.711
13	8.80e-01	1.53e+02	145.7031	1146.983
14	4.90e-01	1.39e+02	160.3236	1265.399
15	2.89e-01	1.26e+02	173.5797	1378.385

The results of the third group show the risk of the COVID-19 pandemic where there are increases in the number of deaths by the time from 0 on the first day until reaching 1378 cases at the end of 15 days.

The following table shows the summary of the *SIRD* model of the third group:

Table (8): Summary of the SIRD model of n =300

	S	I	R	D
Min.	1.84e-03	7.02e-11	0	0
1st Qu.	1.84e-03	9.34e-08	299.7068	5527.81
Median	1.84e-03	1.65e-04	299.998	10013.96
Mean	5.70e+00	1.00e+01	284.2981	9952.941
3rd Qu.	1.86e-03	2.91e-01	299.9982	14498.95
Max.	2.99e+02	2.11e+02	299.9982	18983.93
N	300	300	300	300
sd	3.73e+01	3.40+01	54.14817	5305.774

It is noticed from the table of n = 300 that the data does not belong to the normal distribution and the standard deviation is increased espcially for removed states and death states which refer to extremely dangerous of COVID-19.

The following table shows the Maximum likelihood estimations for the third group:

Table(9): Maximum likelihood estimations of n = 300

Parameter	Estimate	SE
Beta	-10.00111	4.00125
Gamma	-6.32587	2.98651
Sigma 1	5.65891	2.56234
Sigma 2	3.45789	1.98521
Sigma 3	5.75321	2.98433

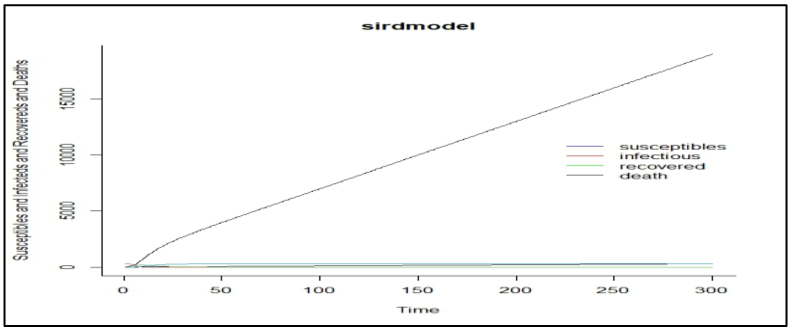

Figure (4): SIRD model at n=300

Figure (4) shows the SIRD model when the sample size equals 300 COVID-19 patients, and it is obvious that the number of deaths increases through time from 0 until reach to 18984 deaths at the end of 300 days which shows the severity of COVID-19.

The Fourth group:

The fourth group consists of 400 COVID-19 patients and their results are as follows:

Table (10): Results of the fourth group n = 400

time	S	I	R	D
1	3.99e+02	1.00e+00	0	0
2	3.95e+02	4.44e+00	0.231009	41.16383
3	3.80e+02	1.91e+01	1.239479	86.26788
4	3.23e+02	7.18e+01	5.291525	146.8113
5	1.95e+02	1.87e+02	17.84486	250.6376
6	7.44e+01	2.84e+02	41.98669	414.2567
7	2.25e+01	3.06e+02	71.94035	609.7038
8	6.76e+00	2.91e+02	101.9329	808.3727
9	2.21e+00	2.68e+02	129.9169	999.9048
10	7.94e-01	2.44e+02	155.4893	1182.057
11	3.14e-01	2.21e+02	178.7091	1354.885
12	1.35e-01	2.00e+02	199.7478	1519.019
13	6.31e-02	1.81e+02	218.7954	1675.2
14	3.17e-02	1.64e+02	236.035	1824.154
15	1.70e-02	1.48e+02	251.6361	1966.556

The results of the fourth group show the risk of the COVID-19 pandemic where there are increases in the number of deaths by the time from 0 on the first day until reaching 1967 cases at the end of 15 days.

The following table shows the summary of the SIRD model of the fourth group:

Table (11): Summary of the SIRD model of n = 400

	S	I	R	D
Min.	4.49e-05	5.92e-15	0	0
1st Qu.	4.49e-05	7.97e-11	399.9719	9419.895
Median	4.49e-05	1.30e-06	400	17400.01
Mean	4.50e+00	1.00e+01	385.5001	17343.1
3rd Qu.	4.50e-05	2.80e-02	400	25380.01
Max.	3.99E+02	3.06e+02	400	33360.01
N	400	400	400	400
sd	3.88e+01	4.07e+01	59.74384	9344.863

It is noticed from the table of n = 400 that the data does not belong to the normal distribution and the standard deviation is increased espcially for removed states and death states which refer to Extremely dangerous of COVID- 19.

The following table shows the Maximum likelihood estimations for the fourth group:

Table (12): Maximum likelihood estimations of n = 400

Parameter	Estimate	SE
Beta	-7.36925	2.11447
Gamma	-3.98752	1.99884
Sigma 1	3.55882	1.56478
Sigma 2	1.96325	0.99876
Sigma 3	2.98754	1.97452

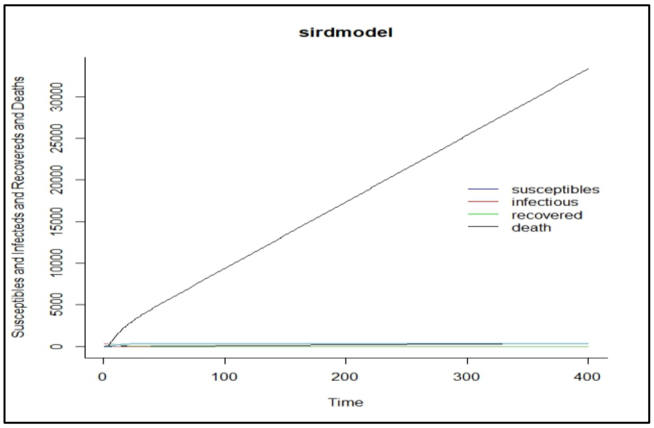

Figure (5): SIRD model at n = 400

Figure (5) shows the SIRD model when the sample size is equal to 400 of the COVID-19 patients and it is obvious that the number of deaths increases through time from 0 until reach to 33360 at the end of 400 days which shows the severity of COVID-19.

The fifth group:

The fifth group consists of 500 COVID-19 patients and their results are as follows:

Table (13): Results of the fifth group n = 500

time	S	I	R	D
1	4.99e+02	1.00e+00	0	0
2	4.93e+02	6.60e+00	0.297429	51.4976
3	4.57e+02	4.08e+01	2.195985	111.0878
4	3.08e+02	1.80e+02	12.03113	210.859
5	1.02e+02	3.59e+02	39.79993	402.1415
6	2.14e+01	4.00e+02	78.68748	652.4711
7	4.49e+00	3.78e+02	117.7692	907.7217
8	1.06e+00	3.45e+02	153.9224	1152.1
9	2.84e-01	3.13e+02	186.8012	1383.557
10	8.62e-02	2.83e+02	216.5905	1602.698
11	2.93e-02	2.56e+02	243.5556	1810.552
12	1.10e-02	2.32e+02	267.9578	2008.159
13	4.57e-03	2.10e+02	290.0388	2196.483
14	2.05e-03	1.90e+02	310.019	2376.403
15	9.97e-04	1.72e+02	328.0979	2548.719

The results of the fifth group show the risk of the COVID-19 pandemic where there are increases in the number of deaths by the time from 0 on the first day until reaching 2548 cases at the end of 15 days.

The following table shows the summary of the SIRD model of the fifth group:

Table (14): Summary of the SIRD model of n = 500

	S	I	R	D
Min.	1.03e-06	4.94e-19	0	0
1st Qu.	1.03e-06	7.21e-14	499.9973	14311.32
Median	1.03e-06	1.05e-08	500	26786.33
Mean	3.77e+00	1.00e+01	486.2265	26731.99
3rd Qu.	1.03e-06	2.67e-03	500	39261.33
Max.	4.99e+02	4.00e+02	500	51736.33
N	500	500	500	500
sd	4.00e+01	4.64e+01	64.67348	14540.29

It is noticed from the table of n = 500 that the data does not belong to the normal distribution and the standard deviation is increased espcially for removed states and death states which refer to Extremely dangerous of COVID- 19.

The following table shows the Maximum likelihood estimations for the fifth group:

Table (15): Maximum likelihood estimations of n = 500

Parameter	Estimate	SE
Beta	-5.56324	1.33661
Gamma	-1.65832	0.95412
Sigma 1	1.96210	0.99665
Sigma 2	0.66523	0.00987
Sigma 3	1.55221	0.69988

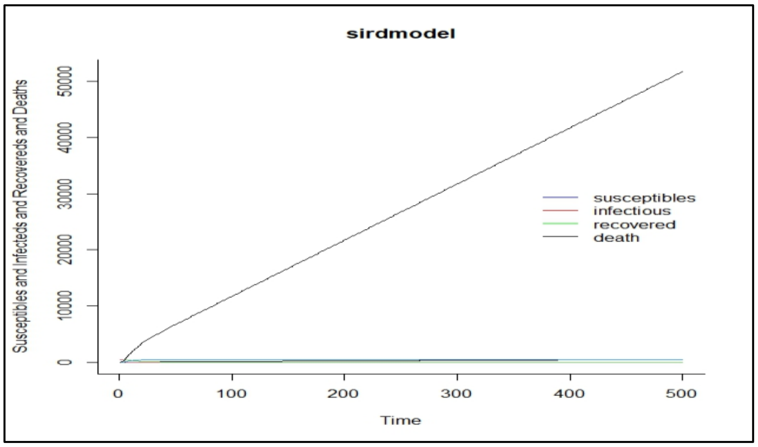

Figure (6): SIRD model at n = 500

Figure (6) shows the SIRD model when the sample size equals 500 of the COVID-19 patients and it is obvious that the number of deaths increases through time from 0 until reach to 51736 at the end of 500 days which shows the severity of COVID-19.

5. Conclusions:

In the present study, observed data of COVID-19 in Egypt in the first year of 2020 is analyzed using SIRD model with an aim to predict the precise description of the disease, such as, the spread of the disease, the probable peak date, the total number of infected, the total number of removed, the total number of deaths, the duration of an epidemic. SIRD model provides a method to investigate the risk of the epidemic disease COVID-19 and contributes to decision making in the face of future epidemics or pandemics. The SIRD mode helps government officials to take precautionary measures to prevent or decrease the risk of any epidemic or pandemic in the future.

From the analysis of COVID-19 data in the study sample:

- Most COVID-19 patients 66% of them has centered in the grade 3 which included: doctors, nursing staff, university teaching staff, engineers, mangers, teachers, officers, computer engineers, businessmen, Lawyers and accountants.
- COVID-19 is more widespread in women than men and most of COVID-19 patients 62% are females, their age range from 20 to 40.
- The study showed that infection with COVID -19 is not affected by medical history which included patient history and smoking.

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