Exploring Dependence of COVID-19 on Environmental Factors and Spread Prediction in India

Hemant Bherwani
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India
Ankit Gupta
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India
Saima Anjum
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India
Avneesh Anshul
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India
Rakesh Kumar
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India

Research Article

Keywords: COVID-19, Coronavirus, SEIR, SARS-CoV-2, Response Surface Methodology, Environment, Temperature, Relative humidity

Posted Date: April 27th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-25644/v1

Version of Record: A version of this preprint was published on September 25th, 2020. See the published version at https://doi.org/10.1038/s41612-020-00142-x.

Exploring Dependence of COVID-19 on Environmental Factors and Spread Prediction in India

Hemant Bherwani[1,2]*, Ankit Gupta[1,2#], Saima Anjum[1], Avneesh Anshul[1,2], Rakesh Kumar[1,2]
[1]CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India
[2]Academy of Scientific and Innovative Research [AcSIR], CSIR-NEERI, Nagpur, India
Corresponding authors E-mail: *h.bherwani@neeri.res.in; # a1_gupta@neeri.res.in

Abstract

The pandemic of "Corona Virus Disease 2019" or COVID-19 has taken the world by storm. Majority of nations of the world have been challenged by the novel coronavirus, which is supposedly of zoonotic origin and is known as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The present work attempts to evaluate the spread of COVID-19 in India. The methodology of assessment uses SEIR (Susceptible-Exposed-Infectious-Removed) model to establish the impact of socio-behavioural aspect, especially social distancing, affecting the numbers of COVID-19 cases per day. The lockdown initiated by Government of India (GoI) scenario is weighed against a scenario with a possible initiation of community spread due to crowded gatherings in India. The resultant changes, as against the lockdown scenario, has been reported in terms of the increase in the number of cases and stretch of the timeline to mitigate the COVID-19 spread. Impact of environmental factors like temperature and relative humidity have also been analyzed using statistical methods, including Response Surface Methodology (RSM) and Correlation. It has been found that the spread of cases is dependent on environmental conditions, i.e. temperature and relative humidity. This study is expected to help the policymakers and stakeholders to device an improved action plan to alleviate the COVID-19 spread, especially in India.

Keywords: COVID-19, Coronavirus, SEIR, SARS-CoV-2, Response Surface Methodology, Environment, Temperature, Relative humidity

Introduction

During the end of December 2019, an outbreak of atypical pneumonia [now being called as coronavirus disease 2019 (COVID-19)] started in Wuhan, China [1-4]. The virus is being considered of zoonotic origin. It is being referred to as severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) or in general referred to as novel coronavirus, and the disease-associated is being called COVID-19 [3-5]. With the onslaught of SARS-CoV-2 in India, major interventions in epidemic preparedness started. These interventions include, but not limited to, public awareness, deployment of widespread testing facilities, medical institutions preparedness, and surveillance and tracking of individual movement and quarantines of suspected cases [6]. Presently social distancing and regularly washing of hands are some of the best ways to keep this virus at bay [7].

Countries all over the world are challenged with this virus and have declared lockdowns in their various cities and states [8-11]. In India, nationwide lockdown is declared for 21 days starting 25th March 2020 [12, 13]. People are instructed to stay indoors unless for emergency services [14]. All tourist visas and e-visas for travellers are suspended till 15 April 2020. Travellers, who returned after 15 February 2020, are quarantined for a minimum of 14 days upon their arrival in India [15]. The researchers estimate that the virus proliferates to more than two persons from every infected person, highlighting the possibility to infect millions [16]. The effectiveness of lockdown is contingent on people avoiding social gatherings and limiting population movement. India reported its first COVID-19 case, originating from China, on 30th January 2020 in Kerala [17]. Government of India (GoI) reported its first COVID-19 death on 10th March 2020 in Karnataka. Till April 5th 2020, India has reported 3577 confirmed cases with 275 recoveries and 83 deaths by COVID-19 [18-20].

Researchers are trying to understand the trend of the SARS-COV-2 movement, to predict the scenarios of new potential cases and to plan effective remediations for their country [21-22]. The role of environmental conditions in the survivability of this virus has also emerged as a potential factor impacting the spread [23-26]. Few studies have suggested that virus should behave similar to most influenza or flu, or also Severe Acute Respiratory Syndrome (SARS), commonly suggesting its reduced activity in hot and humid conditions [27-29]. However, it is essentially necessary to investigate the impact of local environmental conditions, on the virus spread. The alarming community spread of SARS-CoV-2 majorly impacts the public health, economics and behavioural aspect of the society [30]. The susceptible-exposed-infectious-recovered (SEIR models) has been reported as a successful tool to understand the pandemic dynamics and to evaluate the impact of environmental and social conditions on the spread of

COVID-19 [31-34]. Hence, the present work focuses on highlighting the impact of behavioural aspects of the society, and local environmental condition on COVID-19 spread using the SEIR model and statistical tools

Methodology

The present assessments have been carried out in two folds. First is to predict the number of confirmed cases of COVID-19 for India and the time period for its subsidence. Secondly, to evaluate the dependency of COVID-19 spread on environmental factors namely temperature, and relative humidity

The prediction is of COVID-19 cases is based on the SEIR (Susceptible-Exposed-Infectious-Removed) model, which has been used to simulate two practical implementation conditions related to societal behavioural issue. The first case is where the lockdown is followed diligently and the other being with community breaches and failure of social distancing. Both of these scenarios actually happened in India and have been considered accordingly.

The SEIR model for the spread of Infectious disease is simulated, similar to severe acute respiratory syndrome [35]. Immunity, infected, exposure probability and recovery/removal are the compartments of the model [36]. The simple SEIR model with its codes and governing equations are stimulated for India having maximum number of reported COVID 19 cases for understanding efficacy of measures in the current time and future. Governing equations along with the data for various values for S-E-I-R model are given as supplementary data in Annexure I. World Health Organization (WHO), India reported the numerals of COVID-19 pandemic spread in India on a day-to-day basis [17-20]. The primary sources of the data are WHO situation reports for India [37, 38]. Daily migration index has been computed on the basis of mass movements of people from one city to another through various mode of transportation like air, road and rail [16]. SEIR equations are modelled using python program v2.7.5 (open source) to predict the forthcoming Susceptible [S], Exposed [E], Infected [I], Recovery [R] cases for India [39]. The parameters considered with respect to the model are given as follows:

SEIR Model Parameters

Table 1 below gives the SEIR model parameters. Detailed equations and corresponding values are given as supplementary data in Annexure-I

Table 1: SEIR Model Parameters

Parameter	Brief Data Definition	Source/Reference
Suspected people (S[t])	The total number of	Ministry of Health and

	suspected people in India are taken from WHO highlights showing a number of suspected samples for testing out of which some have positive results (SARS-CoV-2).	Family Welfare (MoHFW) [17-20]
Population (N)	Total population data is as per the census report. The population of India is about 133.92 crores	Census of India [40]
Rate of transmission (β_1 and β_2)	The mortality rate of COVID-19 at about 3.434% in China and about 1.1% outside China. Rate of transmission is 1.5 - 4.5 for SARS-CoV-2, which is more than SARS rate of transmission.	[41]
Incubation rate (σ)	2 to 14 days has been publicly reported for SARS-CoV-2	Publicly available report of confirmed cases [42]
Number of contacts per person ($r[t]$)	The number of contacts per person can be considered as the number of exposed people during inflow and outflow of the population it is estimated depending upon population, age group, household size, etc	The daily average number of contacts per person [43-44]
Exposed People (E[t])	The number of exposed people can be calculated by the inflow rate of people coming from other places and the outflow rate of people flowing out of the country.	The latent population of country [45]
Infected People (I[t])	The total number of infected people in the country from January 2020 data is collected from online sources till April 3rd 2020.	WHO pandemic report [36]

The data on confirmed cases for India which have been used in the above model is shown as supplementary data in Annexure-II.

While studying the relation of environmental factors with COVID-19, relative humidity and temperature are considered as the base parameters. The daily rise in COVID-19 cases in various cities of India are correlated with above parameters to understand the relation. In addition to simple correlation, Response Surface Methodology (RSM) is used to establish an empirical association between the metrological parameters, which included Temperature and Relative humidity, over the rising COVID-19 cases in India. The raw data related to statistical modelling is given as supplementary data in Annexure III.

A response surface is used to map the entire cases of the particular region using a full quadratic function. The association of the parameters can be depicted as a second-order polynomial equation.

$$R = \beta_0 + \sum_{i=1}^{i=n} \beta_i x_i + \sum_{i=1}^{i=n} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j \quad (1)$$

where, R is the predicted response; β_0 a constant; β_i the linear coefficient; β_{ii} the squared coefficient; and β_{ij} the product-coefficient, n is the number of factors [46-48]. The significance of the respective parameters is established by Analysis of Variance (ANOVA), which can interpret in terms of P values [47]. The lower the P-value, the higher is the significance of the corresponding parameters. A good model fit can be affirmed with high R^2 value [46-48], which help check the competency of the model. Response surface modelling is carried using statistical software MINITAB 14 [49].

Results and Discussion

1. SEIR Model Output

SEIR Model is simulated for two cases. Case A, where the model has considered the input data till 23rd March 2020 and Case B was modelled with data up to 2nd April 2020. The difference between the two datasets is that India had declared Lockdown on 25th March 2020 after understanding the situation that possible community spread of the COVID-19 cases has started and it is to be curbed almost immediately to flatten the curve [50]. Later on, it emerged that the case is true, as a large number of gatherings were happening during the first and second week of March, the spillover of which is seen at the end of March and early April, given the incubation period of novel coronavirus varies from 2-14 days. [51].

For Case A, within the limit of the available datasets, the rise of the number of COVID-19 cases was gradual. The results for Case A are shown below in Table 2 and Figure 1. Referring to SEIR model equations as supplementary data in Annexure-I, S[t] data is taken from COVID-19 cases in India from supplementary data in Annexure-II and S[t+1], i.e. for the day plus one, is computed through the model.

Table 2: Simulation Result of SEIR model for Case A

Date	S[t+1]	E[t+1]	I[t+1]	R[t+1]

	Number of People			
31-Jan	826	19800	2240	18
08-Feb	1191	14300	1400	14
16-Feb	3864	20300	2000	20
24-Feb	4396	16400	1500	33
27-Feb	4446	12800	1200	22
03-Mar	7112	10980	1000	46
10-Mar	8977	11590	1039	258
17-Mar	10653	16084	1439	289
24-Mar	5207	14239	1270	156
31-Mar	4773	8858	790	205
07-Apr	3361	7111	640	242
14-Apr	1041	4429	393	123
21-Apr	79	856	74	117
28-Apr	50	500	20	127

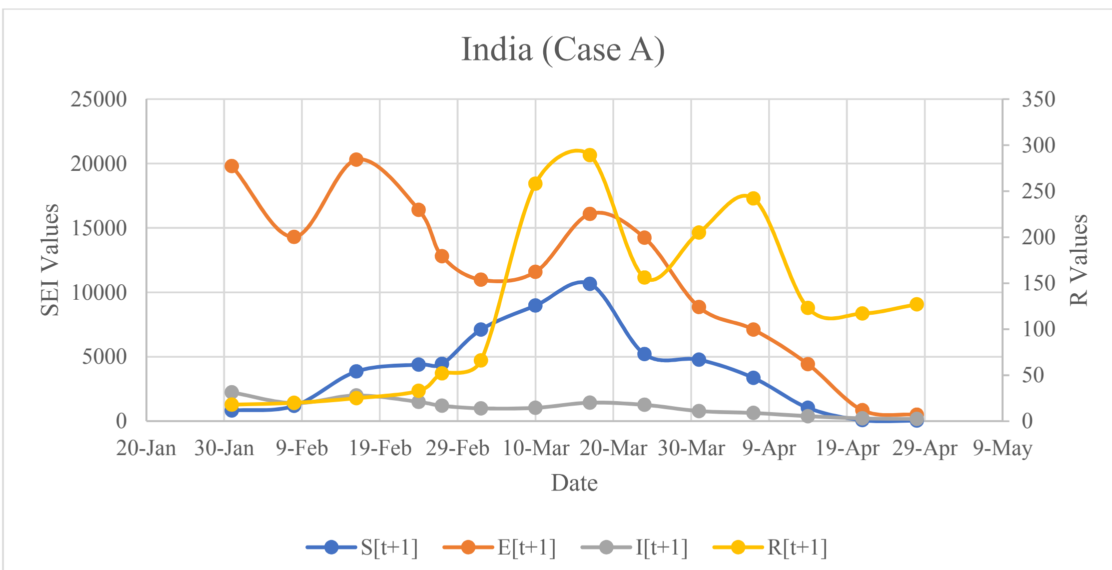


Figure 1: Trend of Rise and Fall of Cases in each category of the SEIR Model (Case-A)

From Table 2 and Figure 1, it can be inferred that if social distancing is strictly implemented to control the community spread, the total number of infected cases is restricted to 15,005. Wherein for Case B, with lapses in social distancing and marking the possible entry to community spread (in the first and second week of March), has given the rise in the number of cases, which is reflected with increased cases at the end of March and start of April. Table 3 and Figure 2 shows that the number of infected cases showed an increasing trend with infection numbers exceeding 18,402 amongst other factors of S, E and R. Not only the number of cases increased but also the overall timeline for stabilization of cases extended by a minimum of 20 days.

Table 3: Simulation Result of SEIR model for Case B

Date	S[t+1]	E[t+1]	I[t+1]	R[t+1]
	Number of People			
31-Jan	826	19800	2240	18
08-Feb	1191	14300	1400	20
16-Feb	3864	20300	2000	25
24-Feb	4396	16400	1500	33
27-Feb	4446	12800	1200	52
03-Mar	7112	10980	1000	66
10-Mar	8977	11590	1039	258
17-Mar	10653	16084	1439	289
24-Mar	5207	14239	1270	156
31-Mar	6054	8858	790	820
07-Apr	7739	13411	1200	1451
14-Apr	2513	10729	945	457
21-Apr	2369	8956	791	177
28-Apr	1505	7191	634	64
05-May	683	5400	486	57
12-May	136	3200	284	85
19-May	82	2100	184	35

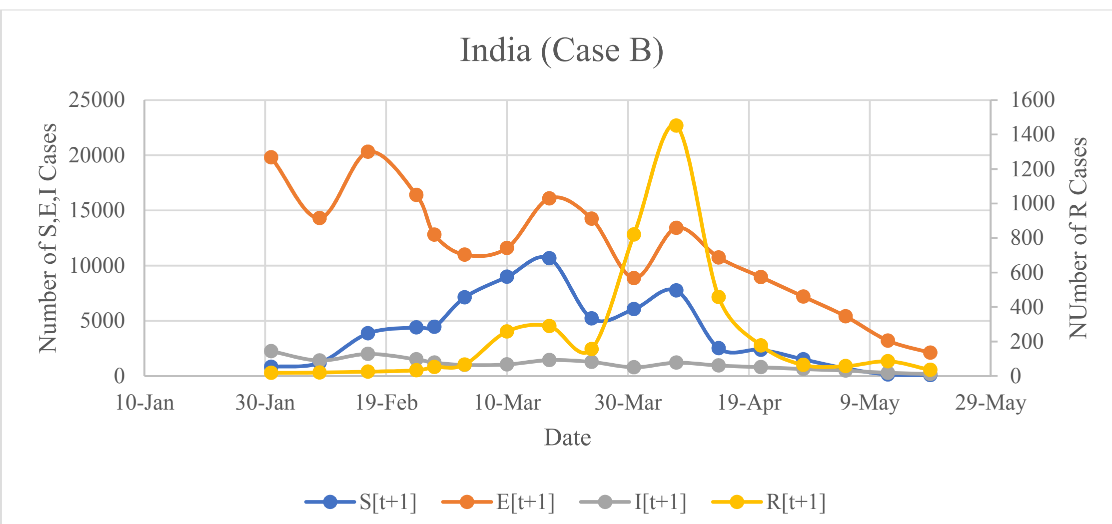


Figure 2: Trend of Rise and Fall of Cases in each category of the SEIR Model (Case B)

2. **Environmental Parameters**

The average state data of temperature and relative humidity are considered to study its relationship in the rising COVID cases in two Indian states, namely; Maharashtra and Karnataka. The range of the parameters under study in these states is tabulated in **Table 4**. These two states have a significant difference in their metrological condition with respect to temperature and relative humidity with T=4.01, P <0.001 and T= 2.71, P-Value = 0.011, obtained from a two-tailed t-test. **Table 5** delineates the results of ANOVA for the cumulative number of COVID-19 cases in the states of Maharashtra and Karnataka, under the varied temperature and relative humidity conditions. From Table 4, it can be inferred that the main effect of the temperature and relative humidity was significant for Maharashtra (F=29.96, P=0.001) and Karnataka (F=6.28, P=0.014). However, the squared effect of the input parameters was seen prominently in Karnataka (F=4.23, P=0.041), which is found negligible for Maharashtra (F=1.54, P=0.254). Also, no significant interaction between the input variables is observed affecting the total number of COVID-19 cases in Maharashtra with F=1.22, P=0.291. However, Karnataka depicts significant interactions between the temperature and relative humidity, impacting the number of cases with F=3.57, P=0.083. The response surface mapped over the cumulative number of COVID-19 cases reflects a good model fit R-Sq of 85.25% and 88.89 % for Maharashtra and Karnataka, respectively. The model fit is also confirmed with low standardized residuals, with good fits for both Maharashtra and Karnataka with lack-of-fit P values as 0.362 and 0.763, respectively. **Figure 3** depicts that modelled inputs data points are in close agreement with normal distribution curve line and residuals are closely distributed at different levels of the independent variable, and hence it can be said that equality of variance exists between varied levels of the response.

Table 4. Range of variable and Coded Units

Parameters	**Range**		**Classifications**	**Coded Unit**
States	Temperature (°C)	Relative humidity (%)	Relative humidity	[-1 to 1]
Maharashtra	27 – 30	37 – 87	< 50 : Low [50-70]: Mid > 70 : High	Low: -1 Mid: 0 High: +1
Karnataka	26 - 28	29 - 88		

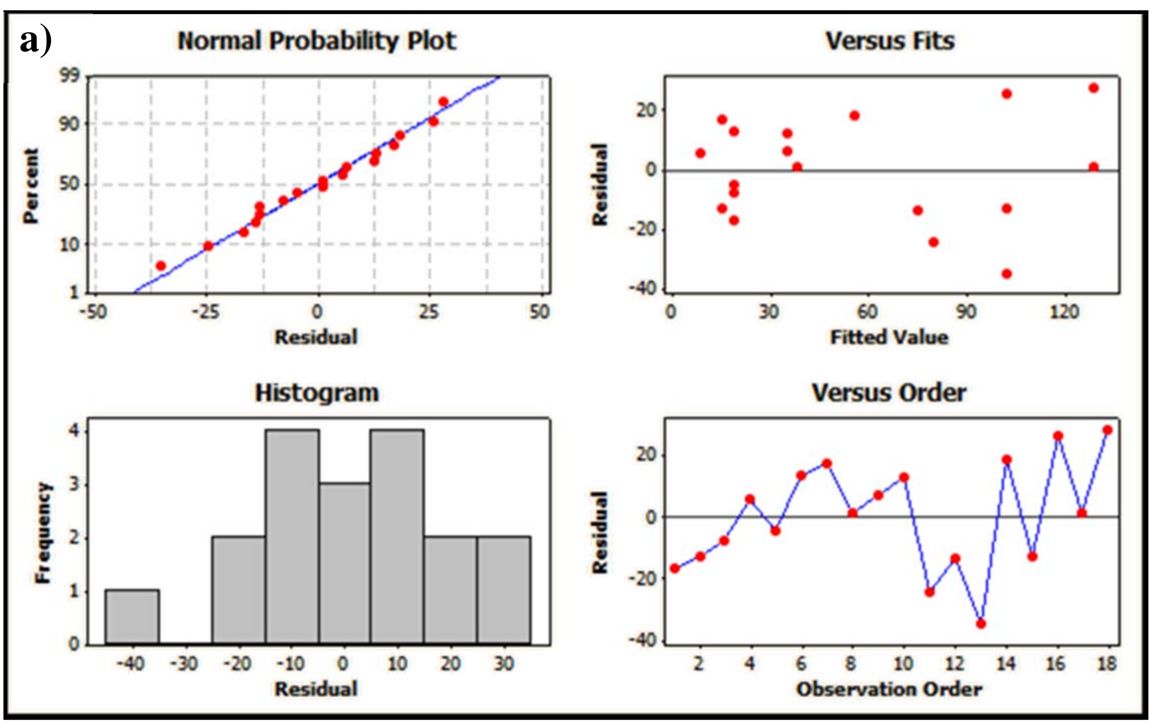
Table 5. Summary of ANOVA results for COVID-19 cases in states of India: (a) Maharashtra (b) Karnataka and (c) T and P values for Maharashtra and Karnataka

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
a) Maharashtra						
Linear	2	28486.9	26155.2	13077.6	29.96	0.001
Square	2	1242.7	1342.6	671.3	1.54	0.254
Intraction	1	533	533	533	1.22	0.291
Residual Error	12	5237.7	5237.7	436.5		

Pure Error	8	3215.9	3215.9	402		
Lack- of-Fit	4	2021.7	2021.7	505.4	1.26	0.362
S = 20.8919 PRESS = 12808.4 R-Sq = 85.25% R-Sq(pred) = 63.92% R-Sq(adj) = 79.10%						
b) Karnataka						
Linear	2	4700.86	678.73	339.36	6.28	0.014
Square	2	292.78	457.28	228.64	4.23	0.041
Intraction	1	192.63	192.63	192.63	3.57	0.083
Residual Error	12	648.18	648.18	54.01		
Pure Error	11	642.58	642.58	58.42		
Lack- of-Fit	1	5.6	5.6	5.6	0.1	0.763
S = 7.34948 PRESS = 1279.17 R-Sq = 88.89% R-Sq(pred) = 78.08% R-Sq(adj) = 84.26%						

Terms	**Maharashtra**		***Karnataka***	
	T	**P**	**T**	**P**
c) ***T and P values***				
Constant	4.187	0.001	1.191	0.257
X1	7.369	0.001	2.577	0.024
X2	0.976	0.348	0.221	0.829
X1*X1	1.377	0.194	2.537	0.026
X2*X2	-0.661	0.521	1.534	0.151
X1*X2	1.105	0.291	-1.888	0.083

Note: X1: Temperature, (°C) ; X2: Relative humidity, %



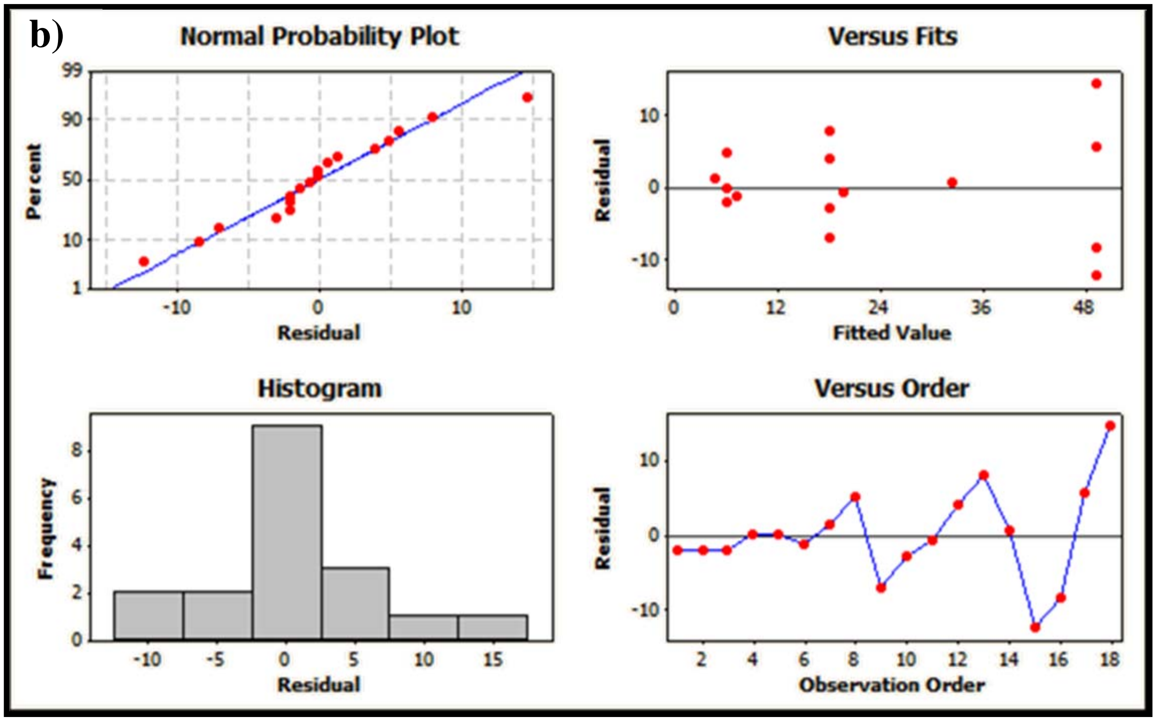


Figure 3: Residual Plots (a) Maharashtra (b) Karnataka

ANOVA, tabulated in **Table 6,** has been performed for Kasaragod city of India also which is supported by the availability of consistent data. The ANOVA results depict the noteworthy impact of the temperature and relative humidity on rising cases per day in Kasaragod. The main effect and interaction effect of relative humidity and temperature are found to be significant with low p-values of 0.054 and 0.035, respectively. Also, as the input parameters are modelled in the coded unit [-1,1], the value of regression coefficients also reflect that the interaction between relative humidity and temperature is dominant on the main effect of the individual factor. The response surface mapped over the new cases in Kasaragod also reflects a good model fit with R-Sq 63.63% (R-S Adj – 53.71%) with low standardized residuals and with lack-of-fit P values as 0.424. **Figure 4** depicting the residual plot of RSM model, confirms that the inputs parameters are in arrangement with the normal distribution line and residual being evenly distributed at all levels of input parameters.

Table 6. ANOVA for new cases per day in Kasaragod

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
d) ANOVA						
Main Effect	2	473	270.91	135.46	3.85	0.054
Intraction Effect	1	203.36	203.36	203.36	5.79	0.035

Residual Error	11	386.57	386.57	35.14		
Pure Error	1	12.5	12.5	12.5		
Lack- of-Fit	10	374.07	374.07	37.41	2.99	0.424

S = 5.92815 PRESS = 13036.2 R-Sq = 63.63% R-Sq(adj) = 53.71%

	Coef.	SE Coef.	T	P
e) ***Regression Coefficients***				
Constant	8.194	3.783	2.166	0.053
X1	-4.418	4.347	-1.016	0.331
X2	5.939	4.383	1.355	0.203
X1*X2	-14.921	6.203	-2.406	0.035

Note: X1: Temperature, (°C); X2: Relative humidity, %

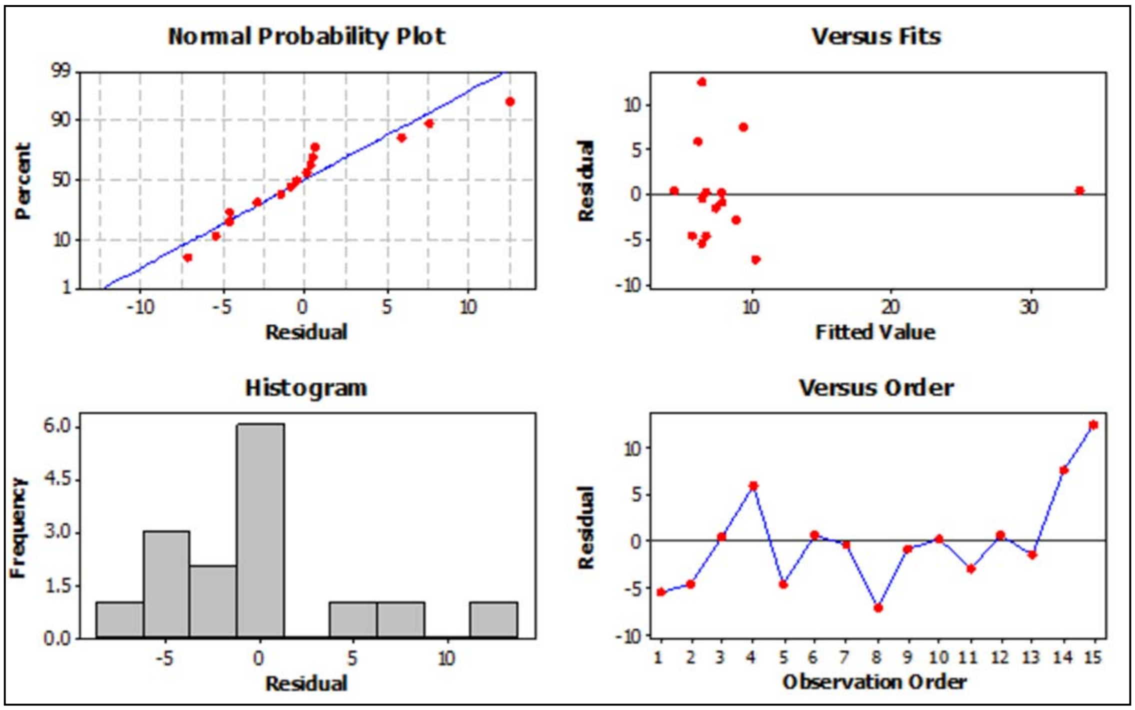


Figure 4. Residual Plot for Kasaragod

In addition to the exploration of the above state and city cases dependency on temperature and relative humidity, statistical correlation is explored for other city cases. Indian cities considered for analysis are Mumbai, Srinagar and Kasaragod. The correlation matrix for each city is shown in Table 7. New York, which has seen unprecedented growth in COVID cases, is also correlated for temperature and relative humidity and validates similar results as Indian cities.

Table 7. Correlation Matrix for Srinagar (A), Kasaragod (B), Mumbai (C) and New York (D)

Srinagar (A)	Temperature	Relative Humidity	Cases/day
Temperature	1.000		
Relative Humidity	-0.815	1.000	
Cases/day	-0.713	0.363	1.000
Kasaragod (B)	Temperature	Relative Humidity	Cases/day
Temperature	1.000		
Relative Humidity	-0.645	1.000	
Cases/day	-0.605	0.607	1.000
Mumbai (C)	Temperature	Relative Humidity	Cases/day
Temperature	1.000		
Relative Humidity	0.442	1.000	
Cases/day	0.495	0.139	1.000
New York (D)	Temperature	Relative Humidity	Cases/day
Temperature	1.000		
Relative Humidity	-0.006	1.000	
Cases/day	-0.277	0.256	1.000

From Table 7, it is observed that most of the cities, except Mumbai, show a similar correlation for the rise in the number of cases per day and environmental parameters, i.e. temperature and relative humidity. The strength of these correlations varied from strong to weak relations, as indicated in Table 7. Within the studied datasets, Srinagar shows the strongest negative correlation with temperature indicating the reduction in the COVID cases with the increase of temperature and a positive correlation with relative humidity. It has been well established that with the increase in temperature, the relative humidity should drop given that the holding capacity of air will increase [52]. Similar correlations can be seen for Kasaragod and New York. However, Mumbai shows a positive correlation with both temperature and relative humidity. This might be due to the fact that as Mumbai is a coastal city and a densely packed one with respect to population and land use. Another reason could be that Mumbai being a metropolitan city and depends on public commutes, making the implementation of social distance practically very difficult. In such cases, the dominance of other factors, for disease spread, on environmental factors cannot be ignored and need separate detailed research. Further, this also confirms that only environmental factors may not be able to mitigate this particular strain of novel coronavirus and other behavioural attributes are bound to pay a major role in its alleviation.

Conclusion

In current time, when every COVID-19 affected nation is making efforts to mitigate and alleviate the spread of this virus, it becomes essential to study the correlations of the rising cases of COVID-19 with respect to behavioural and environmental attributes. India, similar to other countries, is making efforts to curb the spread by strictly monitoring the lockdowns and ensuring social distancing apart from the quest for targeted medical solutions. In a country like India, where the population exceeds 1 billion, social distancing remains a challenging but potential and practically implementable solution. In the current research, an effort is made to establish the impact social distancing to subside the rising cases in India through simulating multiple cases using the SEIR model. The model concluded that breach of social distancing by people engagement in crowded gatherings, with the onset of possible community spread, might result in extending the time to control the spread by minimum 20 days, with a total number of infected cases exceeding 18,40, compared to the normal case of strict compliance of lockdown. The above scenario is considering only a few of the gatherings which occurred in start and middle of March; however, if there are continued gatherings like this, the outcome can be disastrous in terms of number of people infected and respective deaths. Hence, the decision of GoI of nationwide lockdown is very timely to control the spread of the virus. The finding of SEIR helps to conclude that social distancing is one of the best tools available with governments right now to control the spread of this disease.

Also, the impact of environmental conditions is found to be significantly affecting the spread of COVID-19, established through statistical models like RSM and correlation matrices. As temperature rise has been reported to mitigate the spread of viruses, similar trends are observed in most of the Indian cities under the study for SARS-CoV-2. With the present analysis, it is inferred that the hot climate should reduce the spread of COVID-19, whereas relative humidity correlates positively with the number of infected cases. Although a common trend may not be visible right now with respect to environmental factors, it will be wise to find out and understand their correlation in order to support the future action plans It should also be noted that a single model or one prediction methodology may not fit to understand the impact of environmental factors for all the cases of such a geographically large and diverse country like India. The established correlations of COVID cases on environment conditions would aid to prioritize the intervention in the susceptible cities. In future, the model uncertainties should also be explored to continually evolve newer trends to formulate improved predictive sets. It is also important to add environmental parameters into epidemiological models like SEIR to bring out more holistic and unified conclusions assisting policymakers and stakeholder in formulating a comprehensive action plan.

Data availability

The data used in the manuscript is publicly available:

1. Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, Migration Index for India. Retrieved from https://censusindia.gov.in/Census_And_You/migrations.aspx (2nd April 2020)
2. Novel Coronavirus Disease (COVID-19) India Situation Update Report 7, WHO Retrieved from https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-7.pdf?sfvrsn=cf4a7312_2 (14 March 2020)
3. Novel Coronavirus Disease (COVID-19) India Situation Update Report 8, WHO Retrieved from https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-8bc9aca340f91408b9efbedb3917565fc.pdf?sfvrsn =5e0b8a43_2 (22 March 2020)
4. Novel Coronavirus Disease (COVID-19) India Situation Update Report 9, WHO Retrieved from https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-9.pdf?sfvrsn=c883d0c2_2 (28 March 2020)
5. Novel Coronavirus Disease (COVID-19) India Situation Update Report 10, WHO Retrieved from: https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-10.pdf?sfvrsn=48298da5_2 (5 April 2020)
6. Jason Oke and Carl Heneghan. Global Covid-19 Case Fatality Rates, CEBM Research. Retrieved from https://www.cebm.net/covid-19/global-covid-19-case-fatality-rates/ (March 17, 2020)
7. COVID-19 CORONAVIRUS PANDEMIC, Confirmed Cases and Deaths by Country, Territory, or Conveyance. Worldometer. Retrieved from https://www.worldometers.info/coronavirus/#countries
8. 2020 coronavirus pandemic in India, Wikipedia. Retrieved from https://en.wikipedia.org/wiki/2020_coronavirus_pandemic_in_India (March 2020)
9. Coronavirus (COVID-19) map. Google. Retrieved from https://www.google.com/covid19-map/ (3 April 2020)
10. Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, Population data - Census of India: Retrieved from https://censusindia.gov.in/Census_And_You/migrations.aspx (31 March 2020)

11. Thomas Stephens. Coronavirus: Head-shaking doctors and non-hand-shaking workers. Retrieved from : https://www.swissinfo.ch/eng/covid-19_coronavirus--head-shaking-doctors-and-non-hand-shaking-workers/45580772 (26 Feb 2020)
12. COVID-19 Scientific Resources Retrieved from https://www.cerahgeneve.ch/resources/covid-19-free-online-scientific-resources/ (30 March 2020)

Code availability

Any codes used in the paper available upon request from h.bherwani@neeri.res.in

Acknowledgements

Authors thankfully acknowledge Council of Scientific and Industrial Research (CSIR), India and its constituent laboratory National Environmental Engineering Research Institute (NEERI) for support the research.

Author information

Directors Research Cell, CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, 440020, India

- Hemant Bherwani (HB)
- Ankit Gupta (AK)
- Saima Anjum (SA)
- Avneesh Anshul (AA)
- Rakesh Kumar (RK)

Contributions

RK and HB conceived the idea and designed the study with inputs from AA and AG.

SA prepared the data.

HB and AG conducted the analysis and worked on the models using datasets.

AA and SA compiled the results and wrote the initial draft.

HB, AG, AA, and RK improved the discussion and results.

Corresponding author

Hemant Bherwani
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India,
email: h.bherwani@neeri.res.in
and

Ankit Gupta
CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, India,
email: a1_gupta@neeri.res.in

Ethics declarations

Competing interests

The authors declare no competing interests.

The manuscript is checked for plagiarism using licensed iThenticate software wide CSIR-NEERI Knowledge Resource Centre [KRC], CSIR-NEERI/KRC/2020/APRIL/CSUM-DRC-DIR/1 on 08 April 2020.

REFERENCES

1. Novel, C. P. E. R. E. & others. The epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19) in China. Zhonghua liu xing bing xue za zhi= Zhonghua liuxingbingxue zazhi 41, 145 (2020).
2. Wu, F., Zhao, S., Yu, B., Chen, Y., Wang, W., Song, Z., Hu, Y., Tao, Z., Tian, J., Pei, Y., Yuan, M., Zhang, Y., Dai, F., Liu, Y., Wang, Q., Zheng, J., Xu, L., Holmes, E.C., Zhang, Y., 2020. A new coronavirus associated with human respiratory disease in China. Nature, 579(7798), 265-269. https://doi.org/10.1038/s41586-020-2008-3.
3. Zi Yue Zu M, Meng Di Jiang M, Peng Peng Xu M, Wen Chen M, Qian Qian Ni P, Guang Ming Lu M, et al. Coronavirus Disease 2019 (COVID-19): A Perspective from China. doi:10.1148/radiol.2020200490
4. Gorbalenya, A.E., 2020. Severe acute respiratory syndrome-related coronavirus–The species and its viruses, a statement of the Coronavirus Study Group. BioRxiv, 1-15. https://doi.org/10.1101/2020.02.07.937862.
5. Lai, C.-C., Shih, T.-P., Ko, W.-C., Tang, H.-J. & Hsueh, P.-R. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and corona virus disease-2019 (COVID-19): the epidemic and the challenges. Int. J. Antimicrob. Agents 105924 (2020).
6. Bhatia, R. Need for integrated surveillance at human-animal interface for rapid detection & response to emerging coronavirus infections using One Health approach. (2020).

7. Bedford, J. et al. COVID-19: towards controlling of a pandemic. Lancet (2020).
8. Wang, C., Horby, P.W., Hayden, F.G., Gao, G.F., 2020. A novel coronavirus outbreak of global healthconcern. The Lancet, 395(10223), 470-473. https://doi.org/10.1016/S0140-6736(20)30185-9.
9. Sohrabi, Catrin, et al. "World Health Organization declares global emergency: A review of the 2019 novel coronavirus (COVID-19)." International Journal of Surgery (2020).
10. Fisher, Dale, and Annelies Wilder-Smith. "The global community needs to swiftly ramp up the response to contain COVID-19." The Lancet (2020).
11. MacIntyre, C. Raina. "Global spread of COVID-19 and pandemic potential." Global Biosecurity 1.3 (2020).
12. 2020 coronavirus lockdown in India, Wikipedia. Retrieved from https://en.wikipedia.org/wiki/2020_coronavirus_lockdown_in_India (March 2020)
13. Coronavirus: India enters 'total lockdown' after spike in cases, BBC News. Retrieved from https://www.bbc.com/news/world-asia-india-52024239 (25 March 2020)
14. Nolan Pinto. Lockdown is a curfew, only emergency services open. India Today Retrieved from: https://www.indiatoday.in/india/story/coronavirus-lockdown-curfew-bengaluru-police-commissioner-bhaskar-rao-karnataka-covid-19-1658912-2020-03-24 (24 March 2020)
15. India suspends visas in attempt to contain coronavirus spread. Aljazeera Retrieved from: https://www.aljazeera.com/news/2020/03/india-suspends-visas-attempt-coronavirus-spread-200312035057594.html (24 March 2020)
16. Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, Migration Index for India. Retrieved from https://censusindia.gov.in/Census_And_You/migrations.aspx (2nd April 2020)
17. Novel Coronavirus Disease (COVID-19) India Situation Update Report 7, WHO Retrieved from https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-7.pdf?sfvrsn=cf4a7312_2 (14 March 2020)
18. Novel Coronavirus Disease (COVID-19) India Situation Update Report 8, WHO Retrieved from https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-8bc9aca340f91408b9efbedb3917565fc.pdf?sfvrsn =5e0b8a43_2 (22 March 2020)

19. Novel Coronavirus Disease (COVID-19) India Situation Update Report 9, WHO Retrieved from https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-9.pdf?sfvrsn=c883d0c2_2 (28 March 2020)
20. Novel Coronavirus Disease (COVID-19) India Situation Update Report 10, WHO Retrieved from: https://www.who.int/docs/default-source/wrindia/situation-report/india-situation-report-10.pdf?sfvrsn=48298da5_2 (5 April 2020)
21. Boulos, M. N. K. & Geraghty, E. M. Geographical tracking and mapping of coronavirus disease COVID-19/severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) epidemic and associated events around the world: how 21st century GIS technologies are supporting the global fight against outbr. (2020).
22. Khan, N. & Naushad, M. Effects of Corona Virus on the World Community. Available SSRN 3532001 (2020).
23. Jason Oke and Carl Heneghan. Global Covid-19 Case Fatality Rates, CEBM Research. Retrieved from https://www.cebm.net/covid-19/global-covid-19-case-fatality-rates/ (March 17, 2020)
24. COVID-19 CORONAVIRUS PANDEMIC, Confirmed Cases and Deaths by Country, Territory, or Conveyance. Worldometer. Retrieved from https://www.worldometers.info/coronavirus/#countries
25. Poole, Logan. "Seasonal Influences on the Spread of SARS-CoV-2 (COVID19), Causality, and Forecastabililty (3-15-2020)." Causality, and Forecastabililty (3-15-2020) (March 15, 2020) (2020).
26. Graham Lawton, Will the spread of covid-19 be affected by changing seasons? Retrieved from: https://www.newscientist.com/article/2239380-will-the-spread-of-covid-19-be-affected-by-changing-seasons/#ixzz6J9NYfs1c (1 April 2020)
27. Ma, Yueling, et al. "Effects of temperature variation and humidity on the death of COVID-19 in Wuhan, China." Science of The Total Environment (2020): 138226.
28. Oliveiros, B., Caramelo, L., Ferreira, N.C., Caramelo, F., 2020. Role of temperature and humidity in the modulation of the doubling time of COVID-19 cases. medRxiv. https://doi.org/10.1101/2020.03.05.20031872
29. Wang, M., Jiang, A., Gong, L., Luo, L., Guo, W., Li, C.,. & Chen, Y. (2020). Temperature significant change COVID-19 Transmission in 429 cities. medRxiv.
30. COVID-19 Scientific Resources Retrieved from https://www.cerahgeneve.ch/resources/covid-19-free-online-scientific-resources/ (30 March 2020)

31. Chanprasopchai P, Pongsumpun P, Tang IM. Effect of Rainfall for the Dynamical Transmission Model of the Dengue Disease in Thailand. Comput Math Methods Med 2017;2017:2541862. doi:10.1155/2017/2541862
32. Liu T, Zhu G, He J, Song T, Zhang M, Lin H, et al. Early rigorous control interventions can largely reduce dengue outbreak magnitude: experience from Chaozhou, China. BMC Public Health 2017;18(1):90. doi:10.1186/s12889-017-4616-x
33. Niakan Kalhori SR, Ghazisaeedi M, Azizi R, Naserpour A. Studying the influence of mass media andenvironmental factors on influenza virus transmission in the US Midwest. Public Health 2019;170:17-22. doi:10.1016/j.puhe.2019.02.006
34. Shi, Peng, Yinqiao Dong, Huanchang Yan, Xiaoyang Li, Chenkai Zhao, Wei Liu, Miao He, Shixing Tang, and Shuhua Xi. "The impact of temperature and absolute humidity on the coronavirus disease 2019 (COVID-19) outbreak-evidence from China." medRxiv (2020).
35. Shiflet, A. B. & Shiflet, G. W. Introduction to computational science: modeling and simulation for the sciences. (Princeton University Press, 2014).
36. Hethcote, H. W. The mathematics of infectious diseases. SIAM Rev. 42, 599–653 (2000).
37. 2020 coronavirus pandemic in India, Wikipedia. Retrieved from https://en.wikipedia.org/wiki/2020_coronavirus_pandemic_in_India (March 2020)
38. Coronavirus (COVID-19) map. Google. Retrieved from https://www.google.com/covid19-map/ (3 April 2020)
39. Python Software Foundation. Python 2.7.5, release May 12, 2013
40. Office of the Registrar General & Census Commissioner, Ministry of Home Affairs, Government of India, Population data - Census of India: Retrieved from https://censusindia.gov.in/Census_And_You/migrations.aspx (31 March 2020)
41. Thomas Stephens. Coronavirus: Head-shaking doctors and non-hand-shaking workers. Retrieved from : https://www.swissinfo.ch/eng/covid-19_coronavirus--head-shaking-doctors-and-non-hand-shaking-workers/45580772 (26 Feb 2020)
42. Lauer, S. A. et al. The incubation period of coronavirus disease 2019 (COVID-19) from publicly reported confirmed cases: estimation and application. Ann. Intern. Med. (2020).
43. Mossong, J. et al. Social contacts and mixing patterns relevant to the spread of infectious diseases. PLoS Med. 5, (2008).

44. Singh, R. & Adhikari, R. Age-structured impact of social distancing on the COVID-epidemic in India. arXiv Prepr. arXiv2003.12055 (2020).
45. Adlhoch, C. et al. Estimation of the number of exposed people during highly pathogenic avian influenza virus outbreaks in EU/EEA countries, October 2016--September 2018. Zoonoses Public Health 66, 874–878 (2019).
46. Myers, R. H., Montgomery, D. C., & Anderson-Cook, C. M. Response surface methodology: process and product optimization using designed experiments. John Wiley & Sons. (2016)
47. Bower, K. M. Analysis of Variance (ANOVA) using MINITAB. Scientific Computing & Instrumentation, 17, 64-65 (2000)
48. Raj, Ishan, et al. "A high performance biological degradation of trimethylamine: Experimental study and mathematical modeling." Journal of Environmental Chemical Engineering 7.5 (2019): 103292.
49. Minitab Inc. MINITAB statistical software, release 14 for windows (2003).
50. PTI. Lockdown may help flatten India's COVID-19 curve. Retrieved from: https://www.deccanherald.com/national/lockdown-may-help-flatten-covid-19-curve-in-india-says-study-820401.html (2 April 2020)
51. Coronavirus: Search for hundreds of people after Delhi prayer meeting. BBC News Retrieved from: https://www.bbc.com/news/world-asia-india-52104753 (31 March 2020)
52. Fukatani, Y. et al. Effect of ambient temperature and relative humidity on interfacial temperature during early stages of drop evaporation. Phys. Rev. E 93, 43103 (2016).

Supplementary Data

Annexure I

Governing Equations for S-E-I-R model (Susceptible-Exposed-Infectious-Removed) are given as below.

1) $S[t+1] = S[t] + S_{in}[t] - S_{out}[t] - \frac{\beta_1 \times r[t] \times I[t] \times S[t]}{N[t]} - \frac{\beta_2 \times r[t] \times E[t] \times S[t]}{N[t]}$
2) $E[t+1] = E[t] + E_{in}[t] - E_{out}[t] - \frac{\beta_1 \times r[t] \times I[t] \times S[t]}{N[t]} + \frac{\beta_2 \times r[t] \times E[t] \times S[t]}{N[t]} - \sigma \times E[t]$
3) $I[t+1] = \sigma \times E[t] + I[t] - \Upsilon[t]$
4) $R[t+1] = \gamma[t] + R[t]$
5) $S_{in}[t] = In[t] \times (1 - P_{out}[t])$
6) $S_{out}[t] = Out[t] \times (1 - P_{out}[t])$
7) $E_{in}[t] = In[t] \times P_{out}[t]$
8) $E_{out}[t] = Out[t] \times P_{out}[t]$

Where,

S[t] = Number of susceptible people in India

Sin/out[t] = Inflow / outflow of susceptible people based on migration index

β_1 = Rate of transmission from susceptible to infected, 1.5 - 4.5

β_2 = Rate of transmission from infected to imposed

$r[t]$ = Number of contacts per person per day

Before March 9, r = 16, after March 20, r = 6, and after March 23, r = 1

N[t] = The total population of India, 133.92 crores

E[t] = The number of exposed people initially

Ein/out = The number of inflowing/outflowing exposed people

σ = The incubation rate (2-14 days)

$I[t]$ = The number of infected people initially a total of 15 people get affected up till 3rd March

$R[t]$ = The number of recovery or death

$Pout[t]$ = The probability of the outflowing exposed people

γ = The probability of recovery or death

Annexure-II

Data on Confirmed Cases of COVID-19 for India, used in the SEIR Model

Date	Infected I[t]	Death	Susceptible S[t]	Incubation Rate	r[t]	Exposed E[t]
31-Jan	1	0	49	14	12	8000
02-Feb	2	1	1200	14	11	16000
03-Feb	3	0	1741	14	12	20000
02-Mar	5	1	900	14	12	19500
03-Mar	6	0	1021	14	10	18500
04-Mar	28	0	200	14	10	20000
05-Mar	30	4	321	14	8	42000
06-Mar	31	0	420	14	8	48000
07-Mar	34	7	120	14	8	16000
08-Mar	39	0	280	14	8	10000
09-Mar	44	1	358	14	8	12000
10-Mar	50	2	850	14	8	6000
11-Mar	60	0	650	14	4	7200
12-Mar	73	3	120	14	4	1200
13-Mar	81	2	110	14	4	3000
14-Mar	97	0	180	14	4	2000
15-Mar	107	6	426	14	3	1000
16-Mar	118	13	550	14	3	1200
17-Mar	137	3	80	14	3	1200
18-Mar	151	0	80	14	3	1520
19-Mar	173	0	180	14	3	1010
20-Mar	223	0	177	14	3	880
21-Mar	283	0	142	14	3	652
22-Mar	360	3	152	14	3	750
23-Mar	434	0	162	14	3	850
24-Mar	519	1	330	14	3	925
25-Mar	606	2	520	14	3	555
26-Mar	694	0	410	14	3	625
27-Mar	834	0	456	14	3	555
28-Mar	918	1	520	14	3	80
29-Mar	1024	2	440	14	3	20
30-Mar	1251	3	450	14	3	15
31-Mar	1397	1	149	14	3	12
01-Apr	1834	1	142	14	3	8
02-Apr	2069	1	120	14	3	8

Annexure III

Raw data for Statistical Models, used in models. Wherever cases reported are zero, that data point is not considered

	Srinagar			Kasaragod			Mumbai			New York		
Date	Temperature (℃)	Relative humidity (%)	COVID Cases	Temperature (℃)	Relative humidity (%)	COVID Cases	Temperature (℃)	Relative humidity (%)	COVID Cases	Temperature (℃)	Relative humidity (%)	COVID Cases
01-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	4.5	36.5	1
02-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	9.5	49.5	1
03-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	12.0	73.0	2
04-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	10.5	36.0	11
05-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	7.5	38.0	22
06-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	5.0	80.5	44
07-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	8.5	27.0	89
08-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	5.5	33.0	105
09-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	15.0	27.0	142
10-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	15.0	49.5	173
11-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	9.5	41.0	216
12-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	8.0	66.5	325

13-Mar	NU	NU	NU	NU	NU	NU	NU	NU	NU	15.5	78.0	421
14-Mar	NU	NU	NU	NU	NU	NU	25.5	46.5	1	9.5	33.5	613
15-Mar	NU	NU	NU	NU	NU	NU	26	71.5	3	9.0	35.0	729
16-Mar	NU	NU	NU	NU	NU	NU	28	69.5	1	4.0	41.5	950
17-Mar	NU	NU	NU	NU	NU	NU	27	81.5	2	9.0	79.0	1374
18-Mar	NU	NU	NU	NU	NU	NU	27.5	72	1	9.0	41.5	2480
19-Mar	NU	NU	NU	30.0	66.0	1	27	63.5	3	8.5	84.5	5711
20-Mar	NU	NU	NU	30.5	62.0	6	27	78	1	16.5	79.5	8402
21-Mar	NU	NU	NU	30.0	57.0	6	26.5	75.5	8	8.5	36.5	10356
22-Mar	NU	NU	NU	29.0	62.0	5	26.5	85.5	6	4.0	34.5	15168
23-Mar	NU	NU	NU	30.0	62.0	19	28	84.5	13	3.0	89.5	20875
24-Mar	10.5	83.5	1	31.0	61.0	6	27.5	80.5	5	7.5	58.0	25665
25-Mar	10.0	79.0	2	NU	NU	NU	NU	NU	NU	6.0	74.0	30811
26-Mar	10.5	65.0	5	31.0	58.0	3	28.5	86.5	1	7.0	48.0	37258
27-Mar	7.5	90.0	8	26.5	84.0	34	28	83.5	3	15.0	43.0	44635
28-Mar	7.5	79.5	5	30.5	70.0	1	28	64	4	8.5	70.0	52318

29-Mar	13.0	53.5	2	31.0	66.0	7	28	74.5	8	7.0	94.0	59513
30-Mar	NU	NU	NU	31.5	62.0	17	27.5	78.5	5	8.5	79.0	66497
31-Mar	NU	NU	NU	31.0	66.0	2	28	82.5	30	7.0	69.5	75795
01-Apr	NU	NU	NU	31.5	67.0	12	29	74	54	8.0	44.5	83712
02-Apr	NU	NU	NU	30.3	64.8	8	NU	NU	NU	1.5	50	92381
03-Apr	NU	NU	NU	30.3	64.8	7	NU	NU	NU	NU	NU	NU

*NU: Not Used in models, due to zero cases or unavailability of data

Figures

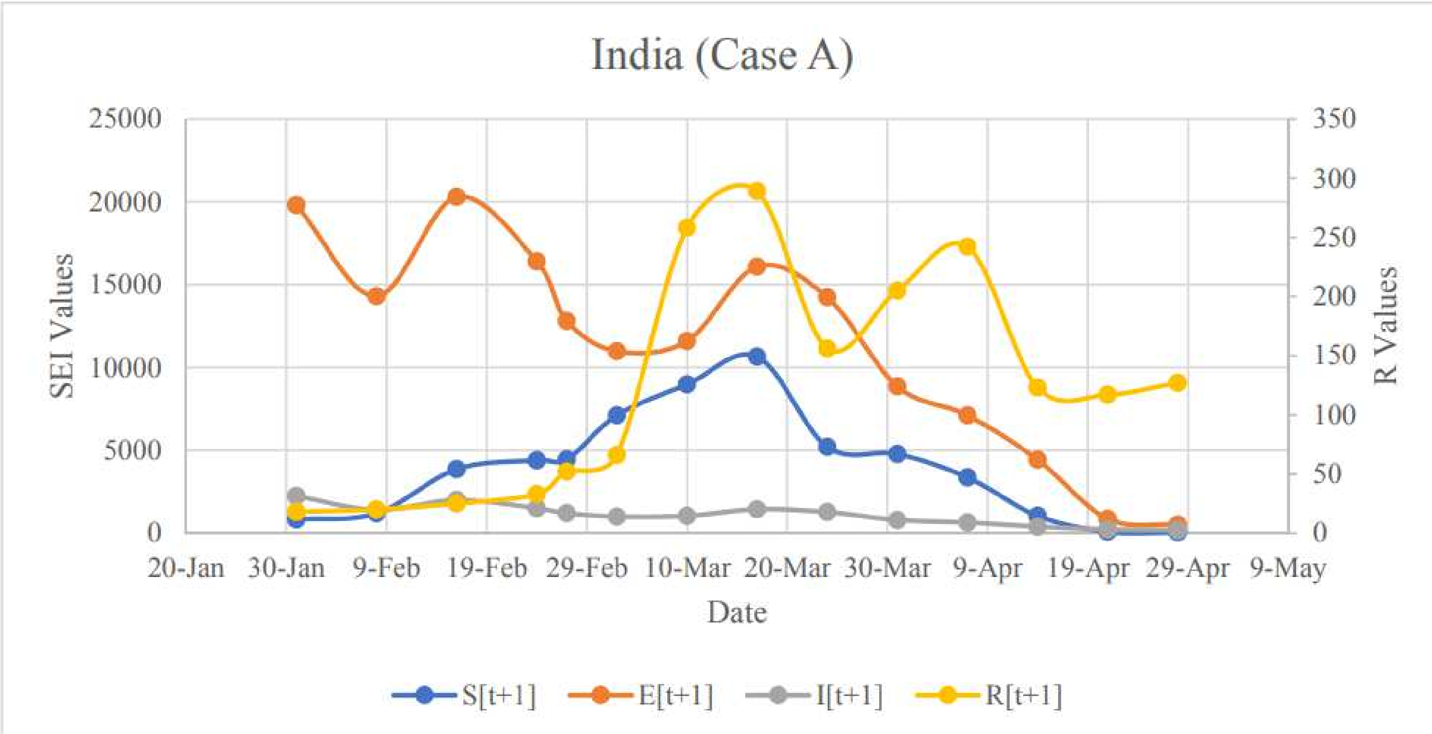


Figure 1

Trend of Rise and Fall of Cases in each category of the SEIR Model (Case-A)

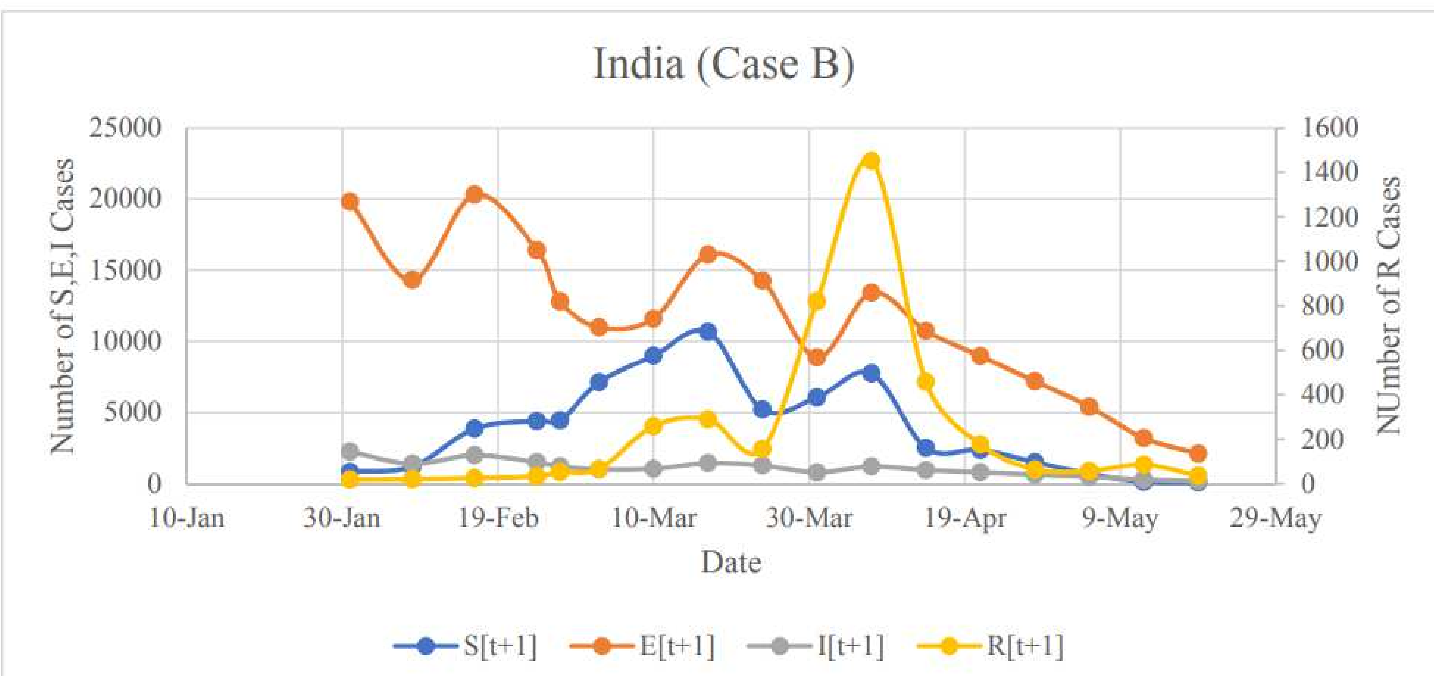


Figure 2

Trend of Rise and Fall of Cases in each category of the SEIR Model (Case B)

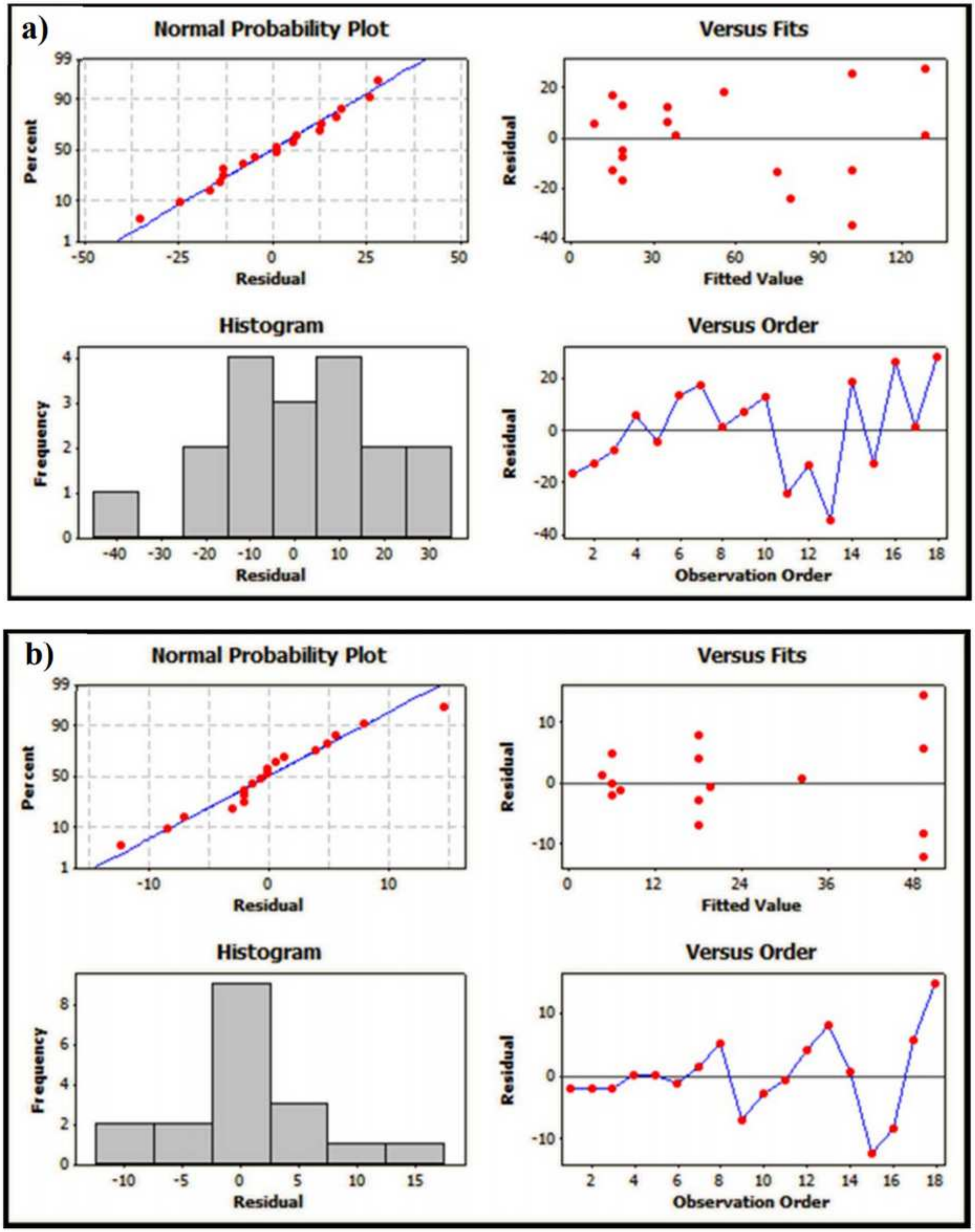


Figure 3

Residual Plots (a) Maharashtra (b) Karnataka

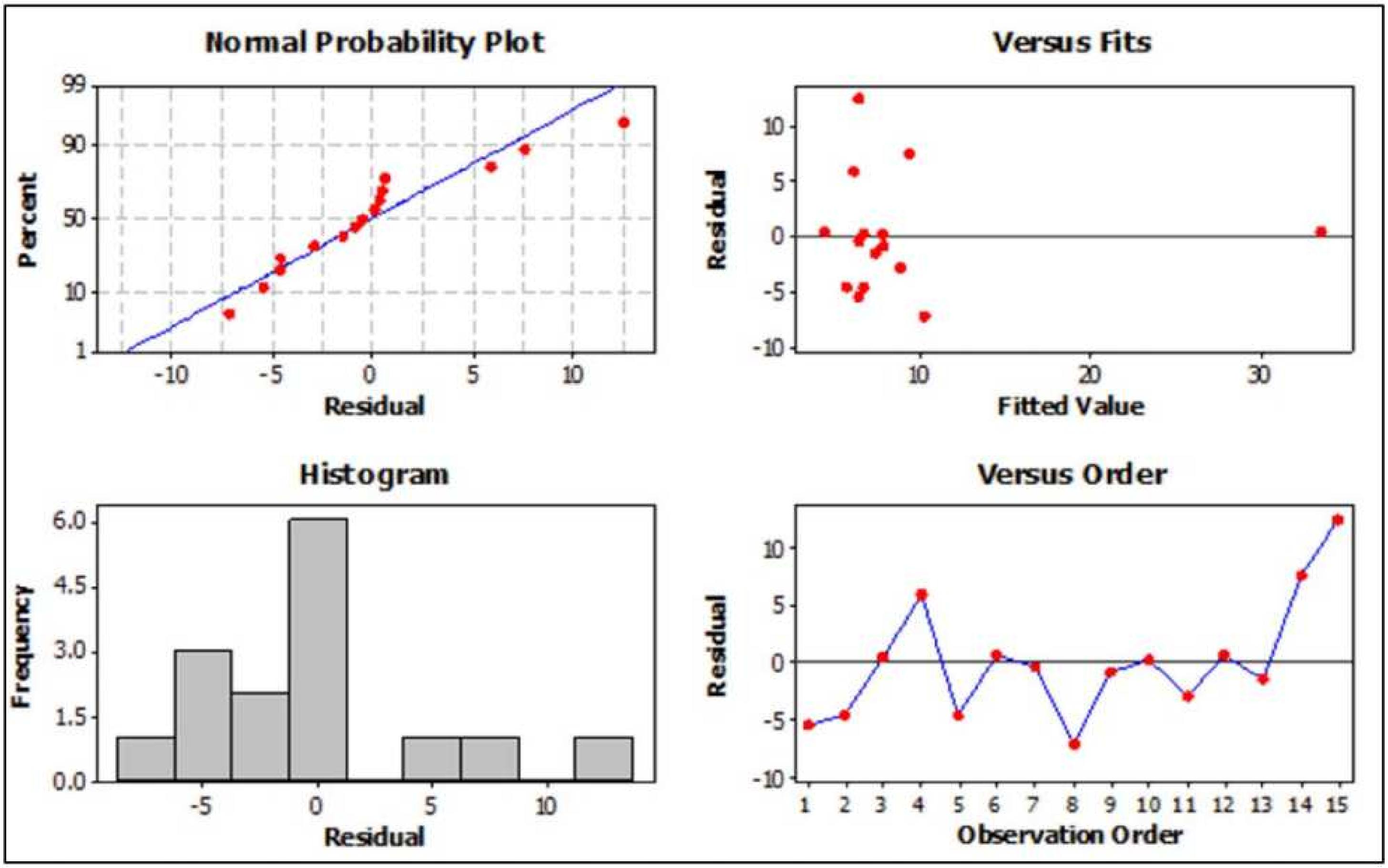


Figure 4

Residual Plot for Kasaragod

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 4530supp11843q8kbmf.pdf
- ANOVATable.docx
- Datasheet.xlsx
- PythonCode.docx