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Editorial

Dynamics of the COVID-19 pandemic: nonlinear approaches on the modelling, prediction and control

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Abstract This special issue contains 35 regular articles on the analysis and dynamics of COVID-19 with several applications. Some analyses are on the construction of mathematical models representing the dynamics of COVID-19, and some are on the estimations and predictions of the disease, a few with possible applications. The various contributions report important, timely, and promising results, such as the effects of several waves, deep learning-based COVID-19 classifications, and multivariate time series with applications.

1 Introduction

Over 200 countries have been affected by the COVID-19 pandemic, resulting in the death of millions of humans. Numerous researchers from different interdisciplinary fields around the world are involved in studies to examine the behavior and nature of the virus and also to develop a potential vaccine against the virus. Several analyses are also focused on "long COVID," and the possible post-COVID conditions and implications for human health and society. Nonlinear tools have been effectively used for the predictions, analysis, and understanding of the dynamics of the pandemic.

This special issue is a compilation of original research articles that address the dynamics and applications of COVID-19 through nonlinear dynamics. The articles are organized in five sections, comprising mathematical modeling and epidemics [1–7], the dynamics of several waves and transmission [8–17], neural network and deep learning related to COVID-19 [18–24], predictions and estimations related to COVID-19 [25–30], and detailed analysis on the pandemic and its applications [31–35].

2 Epidemics and mathematical modeling

This section presents seven research articles on the construction of discrete and continuous mathematical models representing the dynamics of COVID-19.

The dynamics of the spread of an infectious disease together with the economic challenges faced by the country are examined through a combined epidemic–economic model proposed by Karim et al. [1]. Nonlinear analysis of the proposed model is performed along with global stability analysis. They investigate the impact of complete vaccination on reduction in the rate of infections. An epidemic model with the effect of noise is investigated by He and Mukherjee [2]. They study the dynamical behavior and complexity of the stochastic model, and verify the sensitivity of the system with varying noise strength and effect of changes in the initial condition on the noise-induced system. The results can be effective for understanding the uncertainty of a noise-induced epidemic model. A mathematical model of unemployment as a consequence of the COVID-19 pandemic in middle-income countries is developed by Chinnadurai et al. [3], using population dynamics. The results show that the model is effective in controlling unemployment in all kinds of populations.

A discrete time pandemic model is proposed by Ghosh et al. [4] to predict disease outbreak, employing real-world data, and suitable control measures are presented. They claim that in the future, the dynamics of COVID-19 can demonstrate an oscillating behavior. A compartment model of COVID-19 with inclusion of the vaccinated human populations is proposed by Rana et al. [5]. The vaccine reproduction number is obtained, and the study of equilibrium and stability is carried out. The model parameters are estimated by fitting the model with real-time COVID-19 data employing a nonlinear fitting technique. A discrete susceptible-infected mathematical model is proposed by Bashkirtseva and Ryashko [6]. They used a stochastic sensitivity technique to investigate various noise-induced dynamics related to the system. A fractional-order dynamical system is proposed by Khoojine et al. [7] for understanding and predicting the spread of COVID-19 in Thailand. The accuracy of the model in representing

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the real-time data of Thailand is investigated via sensitivity analysis of the model with respect to fractional order.

3 Dynamics of the waves and COVID-19 transmission

Based on COVID-19 transmission, this section presents 10 regular articles on the analysis of the second wave, transmission of airborne viral aerosol droplets, the effect of a contaminated environment, and direct transmission between humans, etc.

The number of infections of COVID-19 in India during the second wave is estimated by Gopal et al. [8] with the help of a four-compartment model comprising susceptible, exposed, infected, and recovered populations. They report that factors such as the individual efforts of people and the support they render to governmental initiatives including the implementation of curfews and vaccination strategies are vital in controlling the pandemic from both a present and future perspective. Based on a nonlinear dynamical model representing the dynamics of the pandemic, Natiq and Saha [9] present the random behavior and unpredictable nature of the COVID-19 outbreak among the prey species and humans infected by the species by means of direct and indirect contact. A simplistic reaction–diffusion model demonstrating the contraction of the virus from contaminated aerosols in a closed room with ventilation is proposed by Turkyilmazoglu [10]. The spatiotemporal dynamics of the aerosol concentration with infectious coronavirus is explored in the article. The necessary safety measures and precautions to be adopted against the risk of infection in the private and public sectors can be framed based on the results they present.

The outbreak of COVID-19 infections in terms of amplitude equations is investigated by Frank and Smucker [11]. The dynamics of the infected population are studied at different epidemic waves; an analytical method is employed to derive the eigenvectors and their respective amplitudes for low-dimensional models, and computational methods are implemented for high-dimensional models. The authors introduce the idea of stages of epidemics, and system behavior is discussed based on the nature of the eigenvectors. In particular, the first wave of the COVID-19 epidemic in the state of New York and in Pakistan is explicitly investigated. A nonlinear mathematical model is proposed by Sarkar et al. [12] to analyze the transmission dynamics of the COVID-19 pandemic in India. The data on daily cases of infection in India are used for model fitting and parameter estimation. The proportional impact of environmental contamination on the increase in infection due to COVID-19 is established, but with disinfection of the environment by sanitation, no drastic increase in the rate of infections is seen. The spread of the coronavirus under the mobility effect in certain regions is investigated by Amoedo et al. [13], and the study focuses specifically on Spain. The way to control inconsistency in the spread of COVID-19 is studied using a regression model. A new method is developed to optimize the usage of data from Google Trends. The results suggest that diversity among the regions is vital in understanding pandemic containment strategies. The impact of cytokine cells in building the immune response against COVID-19 infections is presented as a mathematical model by Rana et al. [14]. An optimal control problem with immunomodulatory therapy is discussed, employing a linear feedback method to improve healthy cells in humans. The results highlight the importance of immunomodulatory therapy in controlling cytokines for restoring the immune system of ill patients and helping them to reach a healthy state.

A COVID-19 transmission model taking into account the direct transmission of the virus between two individuals of which one is infected, together with virus transmission through air, is proposed by Pal and Ghosh [15]. Real-time data of two districts are used to estimate the parameter values employing the nonlinear least-squares technique. The study suggests that increasing vaccination among the susceptible population and treatment of the infected population play a crucial role in containing the disease in the two districts considered. In their work, Ghosh et al. [16] consider an epidemic model of disease spread considering the movement of people and indirect virus transmission by means of a contaminated environment and puff clouds. The numerical calculation of the probability of infection among individuals and survival distances are performed, and values are presented. The influence and impact of the indirect transmission of infection are presented via simulations with respect to several parameters. Based on statistical COVID-19 data, interpretation of multiple waves is studied in the sense of local and global scenarios. A six-compartment mathematical model including the vaccinated, home-isolated, and hospitalized populations together with susceptible, infected, and recovered populations is developed by Devi et al. [17]. The vaccination campaign in controlling the disease spread is given importance by including the impact of speed and effectiveness of the campaigns. The model constructed is validated with real-time data, and the graphical results are presented. The impact of vaccination is studied with data, and the results suggest that isolation and hospitalization are highly necessary until direct transmission among individuals is reduced to a certain level after complete vaccination of every nation.

4 Deep learning and cellular automata related to COVID-19

Chowdhury et al. [18] investigate the spatial and temporal behavior of the disease with the help of a cellular automata (CA) model, and discuss the spread of the disease based on the model. Neighborhood criteria are proposed for measuring the social confinement at the time of the spread of the disease. The model is fitted to the real-time statistical data for different waves in India, and predictions are presented based on infections and social interaction by varying the values of different parameters. In their study, Appasami et al. [19] propose a deep learning-based convolutional neural network (CNN) model with an automatic extraction method for detection of COVID-19 from chest X-ray images collected from different data sources. The chest X-ray images of patients are used for analysis by means of data augmentation, which guides medical professionals in the diagnosis of COVID-19 under their heavy workload situation. Accuracy of 93% is achieved by the choice of best optimizer for classification of COVID-19 data.

In their study, Kumar and Alphonse [20] propose the classification of COVID-19 and other human respiratory sound diseases by a lightweight convolutional neural network with a modified mel-frequency cepstral coefficient (M-MFCC) using different depths and kernel sizes. A comparison between the abnormalities of COVID-19 and other respiratory sound diseases is carried out. Different contextual information supporting the classification of data is obtained as the application of different receptive fields and depths. The authors demonstrated the effectiveness of the classification technique employed with the existing technique and applicability of the technique under different scenarios. The effects of the coronavirus in countries such as India and the USA that exhibit great variation from day to day in cases of infection are investigated by Bhardwaj and Bangia [21]. The study validates the performance measure via mean absolute standard error (MASE), mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE), and coefficient of determination (R^2). The goodness of fit for data values of India and the USA are obtained using wavelet neuronal network fuzzified inferences' layered multivariate adaptive regression spline (WNNFIL–MARS). The authors also suggest that WNNFIL–MARS provides a better fit than the other prediction models.

A new regularized deep convolutional neural network (RDCNN) architecture capable of accepting the sound data and their features is proposed by Kumar and Alphonse [22], and they evaluated the sound data for COVID-19. The proposed model presents a better learning curve in comparison with the other models when trained with COVID-19 sound datasets. Their experimental results suggest that 2–3% greater accuracy in classification for 3×3 kernel size is exhibited by RDCNN (without max pooling) than by RDCNN with max pooling. The authors also suggest that the proposed technique is better suited and achieves better results for respiratory diseases. To determine the effect of lockdown due to COVID-19 on public health, Adak et al. [23] collected data before and after lockdown from 200 random individuals from a municipal region of the state of West Bengal, primarily focusing on six parameters, namely fasting blood sugar, systolic blood pressure, insomnia, diastolic blood pressure, respiratory distress, and cholesterol. A model is formulated using the adaptive neuro-fuzzy inference system (ANFIS) approach with the use of real-time data. The study results suggest that the impact of lockdown on healthy individuals is negligible, while individuals with poor health incur significant effects on health. A knowledge-based approach for the implementation of safety measures to combat the spread of COVID-19 is introduced by Geetha et al. [24]. The analysis is performed based on five different dimensions, including correlating the detected and confirmed COVID-19 cases, speed of detection, maintaining social distance, wearing of masks, and correlating the imported and inbound cases. The actions are based on the level of security in the considered region. The proposed algorithm will serve as a guide to the government for the implementation of several measures, including maintaining sufficient distance among individuals, wearing safety masks, and other policies. This proves to be an effective way to prevent future danger and to implement precautionary policies. Also, the proposed approach will improve the governance of communities.

5 COVID-19-related estimations and predictions

This section presents six regular articles based on prediction analysis related to COVID-19 data.

The article by Biswas [25] aims at real-time prediction of confirmed infections in India and the USA. Neural network autoregression (NNAR)- and autoregressive moving average (ARIMA)-based models are considered for daily data on COVID-19 infections. Their results provide evidence proving that the performance of the hybrid models is better than that of single models. They also present results on advanced hybrid models implementing a wavelet-based approach for better accuracy in assessments (MAE and RMSE). The present situation in India and the USA is illustrated by obtaining a reproduction number that is time-dependent. The aim of the study by Saha et al. [26] is improving the adherence to medication based on active reminders. A detailed study is performed to measure the impact of several factors, including the perception of patients regarding side effects, beliefs, and physician instruction, on medication adherence. These factors play a vital role in improving the rate of adherence. The authors collected real-time data from Sikkim, a state in India. An equation is framed based on the responses obtained from the individuals, and the outcome of the study suggests that there is a significant effect of the importance given by the patients to the physicians and their beliefs. A mathematical compartment model calibrating the effect of the host immune system on COVID-19 infections is proposed by Mondal et al. [27]. They present a mathematical analysis to study the occurrence of the transcritical bifurcation and the analysis of the stability of the steady states. The study also investigates the effect of external factors on the virus reproduction rate, and the formation of backward bifurcation is analyzed. The authors also illustrate the role of the immune system and immunopathology in inhibiting complex epidemic states, and suitable support for the analytical findings is provided by means of simulations.

One of the important aspects of analysis based on multivariate time series is adopted by James and Menzies [28] to understand the state-wise progression of the rate of infection to rate of death in the USA as a function of time. They propose a nonlinear framework to investigate the time-varying offset. The study is performed employing four different approaches, and the results are found to behave in an "up-down-up" pattern and also help in predicting the workload of the healthcare systems and assist in the allocation of sufficient resources to the states in need. Markovian-type models for estimating the spread of the COVID-19 virus in the future considering the exponentially distributed time duration of the population in each compartment of the model are proposed by Basnarkov et al. [29]. The study reveals that the starting time of the infection among individuals coincides with the same time as that of symptoms, while the incubation period is not exponentially distributed. The distribution of the incubation period and the infectivity time period are used to estimate the basic reproduction number (R_0) for COVID-19. The importance of employing the Markovian approach in prediction is presented, and the need for cautious implementation of the method is also suggested. The end time of the pandemic together with the final size, maximum number of populations infected and the time taken to attain the peak infection, and the removal rate of the infected population in China due to COVID-19 are estimated by Pei and Hu [30] with a nonautonomous susceptible–infected–removed (SIR) model with time delay. Though the model appears to be simple and requires very few data, the predictive results are more accurate and effective in reflecting the real-time situation. The results suggest that governmental policymakers can employ several techniques to control the infection rate and improve the economic and social status of the country by increased production and resumption of work.

6 COVID-19-related analysis and applications

This section presents five regular articles based on the analysis and applications of the novel coronavirus.

The article by He et al. [31] implements the theory of multifractals to illustrate the impact of infections at different age groups by classifying X-ray images. The study is performed at different levels of noise using filtered and normal X-ray images for better understanding of lung infections. Denoised and noisy X-ray images are compared for calculating the peak signal-to-noise ratio values and mean absolute error with a median filter approach. Age-based analysis of oxygen levels is performed by constructing three-dimensional (3D) visualization using fractal dimension values. The study also reveals increasing complexity of lung infections among older people in comparison with younger people based on their X-ray images. The rate of increase in infection and death due to COVID-19, introducing the orthonormal basis, is investigated by Chen [32]. The study based on an orthonormal basis reveals several unknown features of the pandemic via Fourier coefficients. The values of the coefficients for a considered sample of countries are ranked as ranking vectors. The countries are then categorized by spectral clustering based on the Manhattan metric. The spectral analysis proves superior to classical analysis techniques in describing the internal structures of the time series. Further, they calculate the approximated numbers of infected individuals and deaths.

The primary goal of the article by Malla and Alphonse [33] is to create awareness among people by educating them in differentiating real information from fake news that is being spread. They investigate several social networking websites including Instagram, Facebook, and Twitter that contain fake data on the spread of COVID-19. Various deep learning techniques are employed to test the fake data from tweets that are categorized. The technique proposed in this article outperforms the most effective deep learning models CT-BERT (COVID-Twitter Bidirectional Encoder Representations from Transformers) and RoBERTa (Robustly Optimized BERT Pre-training Approach) employed for fake COVID-19 data analysis with the help of the multiplicative fusion technique. The performance of the proposed model is superior due its ability to overcome the disadvantages of those techniques, and the results are obtained at an accuracy rate of 98.88% and F1 score of 98.93%. In the work by Samadder and Ghosh [34], a study is carried out considering the stock indices of some influential markets of the countries that experienced major impacts from COVID-19. Six major impacted countries with considerable influence are selected. The authors conclude that the economic growth of those markets will recover when the impact of the COVID-19 virus begins to fade. Thangaraj and Easwaramoorthy [35] present a different characterization of the disease and its severity by comparing denoised and noisy computed tomography (CT) scan images collected from COVID-19-infected patients, implementing the theory of multifractals. Multifractal measures are examined, and the CT scan images are classified and investigated by means of filtered and edge detection methods. The authors employ the Robert, Prewitt, and Sobel edge detection algorithms for the converted images to compute various qualitative measures. The comparison results reveal that the Sobel method provides better classification of the CT scan images of COVID-19-infected patients than the other algorithms due to the greater image complexity exhibited by the Sobel method. The study is supported with some statistical analysis of variance (ANOVA) tests, and simulations such as box plots are provided and the experimental images are explored statistically.

7 Conclusion

The outbreak of COVID-19 changed the human perception of day-to-day life and tested the bounds of medical technology in protecting the welfare of humans. Several approaches and safety measures have been implemented to minimize the countless lives that are being affected. However, public health and educational breaches are evidenced in most countries in which not all citizens have the same opportunities to deal with the pandemic. Therefore, this has led to pervasive consequences, including mental health problems because of the disruption of everyday life routines. This special issue is a collection of 35 research articles providing insight into the spread of the coronavirus and control measures against the COVID-19 pandemic.

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