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A Dynamic Model for Predicting the Impact of Vaccine Avoidance and Health Protocols on the Covid-19 Outbreak

Hamed Jabari[a]*, Hamid Shabandarzadeh[b], Ahmad Ghorbanpour[b]

[a] *Mathematics Secretary of Education, Bushehr, Iran.*

[b] *Department of Industrial Management, Faculty of Business and Economics, Persian Gulf University, Bushehr, Iran.*

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ABSTRACT

The COVID-19 pandemic is one of the most critical issues in the world today. Although many countries have been able to control the infection, much research is still needed to uncover the complex dynamics of virus transmission. This study aimed to utilize a mathematical model for analyzing epidemiological data of infectious diseases, aiming to comprehend their behavior, predict future trends, and investigate the influence of external factors on key indicators. This model extends the Susceptible-Exposed-Infected-Recovered (SEIR) framework by incorporating additional populations, such as vaccinated individuals, asymptomatic cases, and hospitalized patients. It also developed dynamics related to vaccination avoidance behavior and adherence to health protocols. It is coded in MATLAB 2018-b software and is executed for 360 days. The results of the simulation showed that it is not possible to achieve the desired level of immunity from vaccine injection without following health protocols. On the other hand, considering the level of infection, increasing the participation rate in receiving vaccines and reducing the population of vaccines can control the epidemic. Therefore, a change in social behavior and an increase in the amount of vaccination can increase the awareness of society in reducing the avoidance of vaccination and improving compliance with health protocols.

Keywords

A dynamic system, SEIR model, COVID-19 pandemic, Vaccination avoidance.

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***Corresponding author**
Email: h_jabbari@mehr.pgu.ac.ir r

1. Introduction

In December 2019, in Wuhan, China, a new strain of the coronavirus (COVID-19) was identified as an epidemic in humans and gradually spread throughout the world to become a pandemic (Zhonghua et al., 2019). About 20 months after its release, the world has seen several mutations in the virus. More than 230 million people have been infected, and 4.8 million have died from coronavirus (Makhoul et al., 2021). During all this time, experts and scientists from different countries have tried to find ways to fight the virus. Some of them have succeeded in producing approved vaccines, such as Pfizer, Moderna, Astrazneka, and Sinopharm, and have made them available to others (Saporta-Keating and Nyquist, 2021; Mallapaty and Callaway, 2021; Mallapaty, 2021; Waheed et al., 2022). Experts emphasize various preventive measures to combat the spread of COVID-19. Alongside widespread vaccination, these measures include strict adherence to health procedures and protocols, practicing social distancing, and avoiding gatherings, particularly weddings and mourning ceremonies. It is observed that vaccines are not welcomed by some people in the world, and protests are even initiated by them to avoid receiving them. (Dror et al., 2020, Chou and Budenz, 2020, Chadwick et al., 2021, Loomba et al., 2021). The results of a survey by the European Foundation for the Improvement of Working and Living Conditions (Euro found) show that nearly a quarter of those surveyed are reluctant to receive the vaccine. The vaccine avoidance population in Western Europe is much smaller than in Eastern Europe, with less than 10% of Danes and Irish people opposed to vaccination, with the highest vaccine avoidance rates in Bulgaria at 59%, France at 38%, and Austria at 34% (eurofound, 2023). In Iran, the results of a poll conducted by the National Planning Office of the Institute of Culture, Arts, and Communications of the Ministry of Culture and Islamic Guidance show that 73.7% of Iranians are willing to be vaccinated against coronavirus (ricac.ac, 2023). However, doctors prefer the benefits of vaccination to its side effects. In addition to emphasizing vaccination, they also require adherence to health protocols until the complete eradication of the coronavirus. Iran also pursued a policy of producing and importing vaccines. The outbreak of the delta species, the inability to mass-produce, and the non-compliance of countries' parties to the vaccine contract marked a dark summer in the country (Barmparis and Tsironis, 2020, Khankeh et al., 2021, Basiri and Koushki, 2021). Considering the recent advancements and rapid implementation of the overall vaccination plan, the significant impact of administering vaccines against COVID-19 allows for making predictions based on dynamic modeling, with a specific emphasis on the vaccinated population. Several methods have been used to predict the COVID-19 trend. Some researchers have used Autoregressive Integrated

Moving Average (ARIMA) statistical models and other regression methods to predict the spread of new epidemics.

Mathematical modeling as a powerful tool for epidemiological analysis of infectious diseases to understand the behavior and forecast and study the impact of external factors on its indicators is clear. The use of differential equations and the design of dynamic systems based on classical models Susceptible-Infected-Recovered (SIR) and SEIR have been considered by many researchers. The researchers used the developed SIR model to determine and predict the peak times of COVID-19 cases and to study the epidemic trend in China, Italy, and France (Fanelli and Piazza, 2020). We can mention the new models presented based on the SEIR model for predicting, examining, and analyzing the behavior of COVID-19 disease (Li et al., 2021b, Partohaghighi and Akgül, 2021). One of the approaches that play a crucial role in controlling the disease and public health in the world is the quarantine strategies defined by the World Health Organization during this COVID-19 epidemic. A group of studies developed classical dynamic mathematical models to predict the impact of quarantine policy on the disease process (Chung and Chew, 2021, Cui et al., 2020, Díaz and Henríquez, 2021, Zhu and Zhu, 2021, Kristjanpoller et al., 2021).

Vaccination has been used as another pandemic control strategy in two ways in mathematical modeling. Some researchers have considered vaccination as a rate variable affecting the recovery of susceptible individuals (Amouch and Karim, 2021, Asgary et al., 2020, Libotte et al., 2020). As the vaccination process increased, the vaccinated population was considered a state variable in the dynamically developed models. The proposed model of SIRDV in (Usherwood et al., 2021), with susceptible (S), vaccinated (V), infectious (I), recovered (R), and deceased populations (D), incorporates two different dynamic population behaviors of the level of caution and sense of security It is possible to predict the course of the disease by vaccination and considering these two behaviors. Foy et al. (2021) and Boudaoui et al. (2021) simulated the SEIR model with a structure of mass communication with social contact matrices to investigate the relative reduction of mortality and the development of vaccine allocation strategies based on the prioritization of different age groups and the interaction of these strategies with simultaneous drug interventions have been performed. Regarding the implementation of the overall vaccination plan, the positive effect of vaccination on COVID-19 is significant to provide predictions based on dynamic modeling focusing on the vaccinated population.

In line with the importance of the present study and learning from the past for future predictions, it should be noted that the global spread and epidemic of the new coronavirus

(COVID-19) has put one of the most critical conditions in front of the country's health service delivery system. The difficulty of managing this crisis, especially with Iran's special conditions, the unknown nature of the disease, and the lack of sufficient experience, has provided the field with creativity and various innovations. Innovative actions, favorable forecasts, valuable experiences in the case of management with smart and innovative approaches and turning into explicit knowledge, and the design of strong decision support and forecasting systems for decision-making are valuable reserves at one's disposal. The health service delivery system of the country and the world will be placed. In addition, the genetic mutations of the virus and the occurrence of several disease peaks in our country and the world confirm the need for scientific planning. The spread of the coronavirus in the world and unpreparedness to face it have caused many problems in the healthcare system of many countries. In this regard, epidemic models are developed, and other components are added.

2. Methodology

Mathematical modeling based on dynamic equations is a powerful tool for epidemiological analysis of infectious diseases to understand behavior, predict, and study how external factors affect them. Compared to statistical methods, it can provide a more precise mechanism for epidemic dynamics and essential information about the disease. The need for this is especially evident in diseases such as COVID-19, where the main epidemiological parameters are unknown or need to be understood more mechanically. Widespread vaccination against coronavirus worldwide is necessary to study vaccinated individuals' behavioral dynamics. In this regard, in this study, vaccinated individuals are considered, and the SEIR model is developed inspired by the models presented in Mallapaty (2021) and Mallapaty and Callaway (2021). As shown in Figure (1), the overall SEIR framework is expanded by the model, which adds vaccinated, asymptomatic, and hospitalized populations and combines dynamics based on vaccination avoidance behavior and observance of health protocols as important defining features of this study.

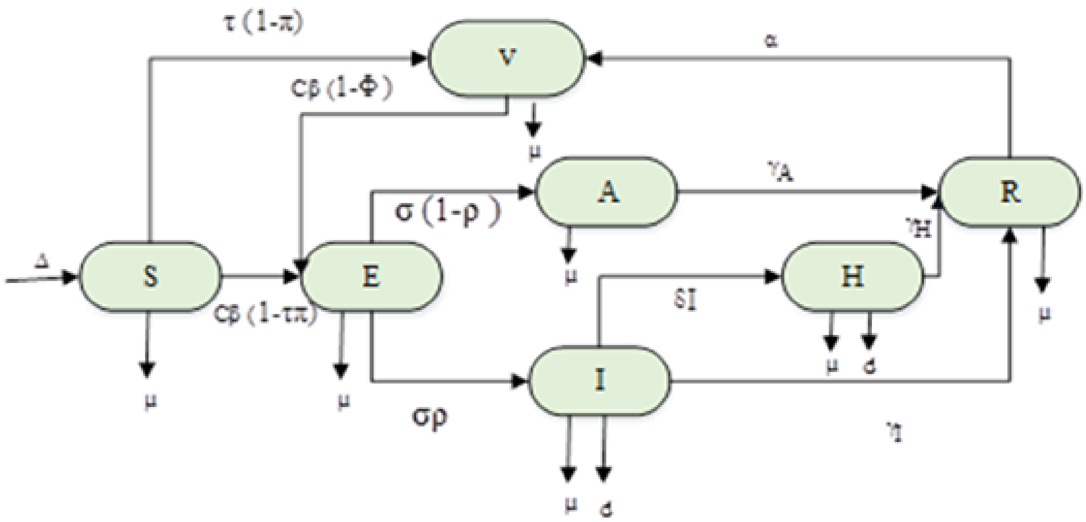

Figure 1. *SVIAHR Model*

This model consists of seven sections: susceptible (S), exposed (E), vaccinated (V), infectious (I), asymptomatic(A), hospitalized(H), and recovered (R). They show S, V, I, A, H, R, and time-dependent fraction variables concerning the area's total population (Table 1). We describe the model starting from the susceptible population. Individuals can be exposed to infection at a rate of β, susceptible populations that are not exposed to the vaccine depending on the availability of the vaccine. Another factor influencing the vaccination rate is the level of public participation or vaccine avoidance. Vaccinated populations, such as the susceptible population, can also be exposed, depending on the vaccine's effectiveness. In this study, the effectiveness of the vaccine (φ), the rate of vaccine availability (τ), and the rate of vaccine avoidance (π) were assumed. The exposed population is transferred to symptomatic patients with a transfer rate of $\sigma(1-\rho)$ and with a transfer rate of $\sigma\rho$ to the compartment of symptomatic patients, which σ is the rate of transmission from E to I and ρ the probability of symptoms in patients. The proportion of asymptomatic infection in the population equal is θ. A fraction of the infected population needs to be hospitalized and is transferred to the H compartment at a rate of δ_I. Populations I, A, and H recover with the transfer rates $\gamma_I.\gamma_A.\gamma_H$. Recovered patients can be vaccinated at a rate of α after 42 days. We consider the natural mortality rate μ for all populations in and corona deaths for the population H, I with d rate. In the present study, τ is the vaccine availability rate and π the vaccine avoidance rate. The simultaneous dynamics of observance of health protocols and vaccination avoidance rates are investigated by performing several different simulations.

Table 1. Compartments of the SVIAHR model with its definitions

Compartments	Definitions
Susceptible population (S)	The ratio of the population who are susceptible to getting infected if they are exposed to it.
Exposed population (E)	The ratio of the population exposed to the infection, but they have no clinical symptoms.
Vaccinated population (V)	The ratio of the population fully vaccinated against Covid-19 relative to the total population
Iinfectious population(I)	The ratio of the population who are infectious and they have clinical symptoms.
Asymptomatic population(A)	The ratio of the population with no clinical manifestations of COVID-19, such as fever, cough, sore throat and other self-perceived or clinically identifiable symptoms and signs.
Hospitalized population (H)	The ratio of the population who were admitted to the hospital due to the infection of covid-19
Recovered population (R)	The ratio of the population who are recovered from the infection and are temporarily immune from the infection.

The rate of reinfection caused by the virus is very low, and its effect can be ignored at the time scale of our study. Due to the uncertainty about the availability of vaccines that will be used in the future, to predict, we have used a fixed vaccination rate and implemented the model according to the rate of different vaccine avoidance under several scenarios. The SVIAHR model for a region /population is described by Equations (1) to (7).

$$\frac{dS}{dt} = \Delta - c\beta(1-\tau\pi)S(I+\theta A) - \tau(1-\pi+\mu)S \quad (1)$$

$$\frac{dE}{dt} = c\beta(1-\tau\pi)S(I+\theta A) + c\beta(1-\varphi)V(I+\theta A) - (\sigma+\mu)E \quad (2)$$

$$\frac{dI}{dt} = \sigma\rho E - (\delta_I + \gamma_I + d + \mu)I \quad (3)$$

$$\frac{dA}{dt} = \sigma(1-\rho)E - (\gamma_A + \mu)A \quad (4)$$

$$\frac{dV}{dt} = \tau(1-\pi)S - (1-\varphi)c\beta V(I+\theta A) - \mu V + \alpha R \quad (5)$$

$$\frac{dH}{dt} = \delta_I I - (\gamma_H + \mu + d)H \quad (6)$$

$$\frac{dR}{dt} = (\gamma_I I + \gamma_A A + \gamma_H H) - (\alpha+\mu)R \quad (7)$$

The summarizes the interpretation of the parameter embedded in the SVIAHR model in Table 2.

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Table 2. The summarizes the interpretation of the parameters

Parameter	Definitions	Estimated Mean Value	Unit and calculation	Data Source
Δ	Birth rate	0.00004	$\frac{\text{birth}}{\text{population}/\text{yearly day}}$	(Sabteahval, 2023)
μ	Natural death rate	0.000013	$\frac{\text{death}}{\text{Population}/\text{yearly day}}$	(Sabteahval, 2023)
c	Contact rate	9.191	Number of individuals Direct contact per person per day	(Shakhany and Salimifard, 2021)
β	Probability of transmission per contact	0.102	-	(Shakhany and Salimifard, 2021)
τ	availability vaccination rate	1/80	Estimated	Experts
π	Vaccine avoidance rate	-	Scenario base	Experts
ρ	Probability of having symptoms among infected person	0.8683	-	(Usherwood et al., 2021)
σ	The transition rate of E to I or A	1/7	1/day	
δ_I	The transition rate of I to H	0.00006	Probability of hospitalized × 1/day	
γ_A	The recovery rate of A to R	0.0714	1/day	
γ_I	The recovery rate of I to R	0.06821	Probability of Recovery ×1/day	
γ_H	The recovery rate of H to R	0.974×1/7	Probability of Recovery × 1/day	(Jabari, 2022)
θ	Infectiousness rate due to A class	0.0205	-	(Usherwood et al., 2021)
d	The death rate from coronavirus	0.026×1/7	Probability of due covid × 1/day	(Jabari, 2022)
φ	The effective rate of vaccination	0.88	Average of several vaccines	
α	The transition rate of R to V	1/42	1/day	Experts

2.1. Data description

The parameters used to implement the model include demographic information on Iran, global rates of COVID-19, and the opinions of health professionals. Birth and natural death rates are calculated based on pre-release data on COVID-19 in Iran (Waheed et al., 2022). Because of the rate of access to the vaccine, the degree of effectiveness in different virus strains is unknown. According to health system experts, it is considered approximately according to Table 2. Recovery rates are based on the average duration of normal recovery or hospitalization and the likelihood of recovery or death from COVID-19 according to data from the delta virus species at the fifth peak of the disease in August and June 2021 in Iran (Chou and Budenz, 2020). Other transfer rates are based on COVID-19 global data, some of which have been modified by experts due to the special conditions of Iran and the widespread prevalence of Delta species. Other transfer rates are based on COVID-19 global data (Chou and Budenz,2020, Usherwood et al., 2021), some of which have been modified by experts due to the special conditions of Iran and the widespread prevalence of Delta species. One of the most critical parameters of the model is β_0 to investigate the effect of health protocol compliance on the system in several scenarios, its initial value is defined as the product of the contact rate in the probability of disease in each contact.

3. Simulation results

The presented model is coded in MATLAB 2018-b software and is executed for 360 days in exchange for Table 2 parameters. It is solved to the ode45 function on the time interval [0 360] with initial values (0.980876, 0.0001, 0.00002, 0.000004, 0,0,0). In this research, simulation is performed with two approaches. In the first step, the rate of vaccination avoidance is fixed, and the rate of disease transmission is assumed to be variable to affect the observance of health protocols. In the second step, the vaccination rate changes by considering the appropriate rate of β. The results are presented in Figure 2. Due to the small scale of the hospitalized variable, this figure is not displayed and presented separately in Figure 3(a).

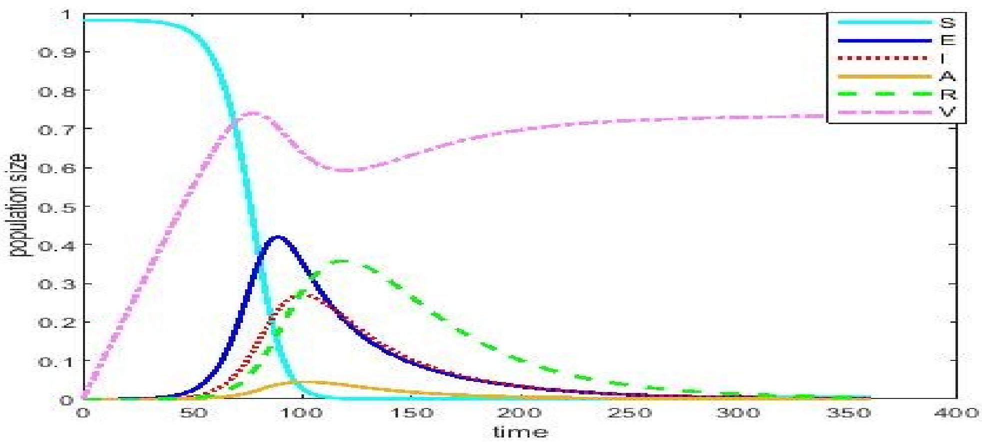


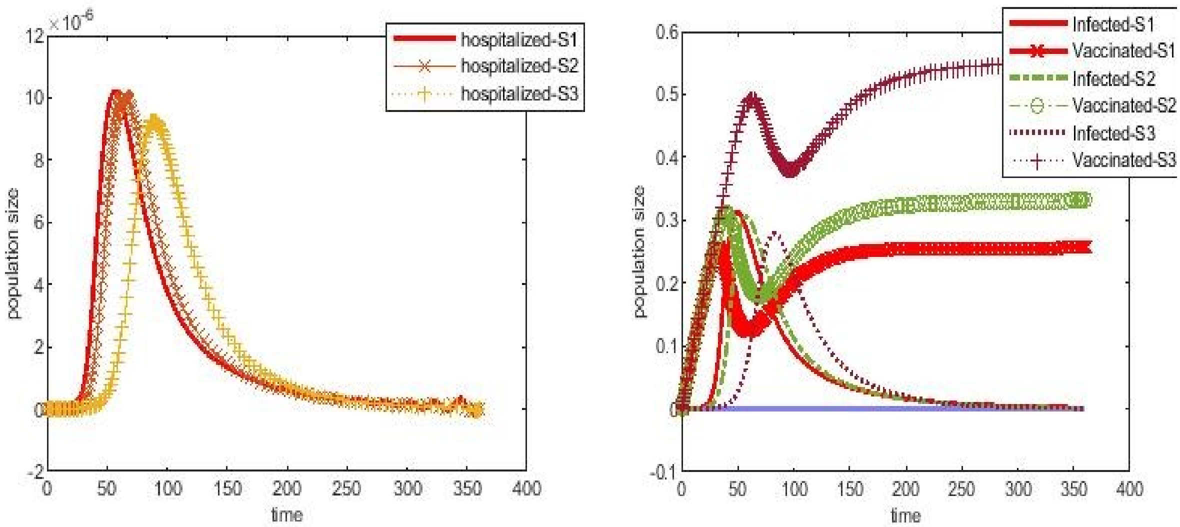
Figure 2. The behaviour of model variables

Next, it is evaluated the effect of increasing the observance of health protocols on the implementation of successful vaccination. Proper vaccination procedures can greatly help manage possible corona peaks in the future. But we must not forget that this period of normalization of the people can also create major problems for the adopted policies and challenge some decisions. Serious adherence to health protocols, social distancing, and reduced contact rates to plan vaccination are necessary. In this study, the extent of changes in contact rates and adherence to health protocols, which reduces the incidence of the disease, on the behaviour of the designed system, with emphasis on indicators of hospitalized, infected, and vaccinated populations, are examined. We examine the effect of β reduction on system behavior, assuming that vaccination avoidance rates and availability are constant. Increasing the observance of hygienic protocols, i.e., using a mask, a physical distance of 1.5 to 2 meters, no formation of any accumulation, proper ventilation, and avoiding the presence of a large number of people indoors can help reduce the incidence rate β. In this section, all simulations are performed for π= 0.75. The system is designed and implemented for $\beta_0, 0.75\beta_0, 0.4\beta_0$. Figure 3. (a) shows the simulation results of hospitalized cases. Figure 3. (b) shows the proportional population of infected and vaccinated for $\beta_0, 0.75, \beta_0, 4\beta_0$. Table (3) shows values of Max hospitalized, Mean hospitalized, Peak time of hospitalized, Max Infected, Mean Infected, Peak time of Infected and Max vaccinated for comparison.

Table 3. Values of indices

Comparison indices	β_0	$0.75\beta_0$	$0.4\beta_0$
Max hospitalized	1.02e-05	1.004e-05	9.207e-06
Mean hospitalized	3.473e-06	3.428e-06	2.73e-06
Peak time 0f hospitalized	56	64	90
Max Infected	0.3121	0.3052	0.2782
Mean Infected	0.1132	0.1078	0.0823
Peak time 0f Infected	49	57	84
Max vaccinated	0.2565	0.3313	0.5528

In Figure 3. (a). hospitalized.S1, S2 and S3 shows hospitalized for $\beta_0, 0.75\beta_0, 0.4\beta_0$ respectively. According to the values presented in the second and third lines of Table 3 and Fig. 3. (a) By reducing the amount β, their number decreases and causes a time delay in the maximum of patients. In Figures 3. (b) a proportional representation of the vaccinated and infected population is performed under three scenarios.



(a) Hospitalized population in 3 scenarios **(b).** Proportional population I and V in 3 scenarios

Figure 3. Proportional population h, I and V in 3 scenarios

Careful examination of figures and comparison of Table 3 values indicate that the reduction in the rate β as a result of following the health protocols as much as possible will reduce the number of hospitalized and infected, the delay in the peak time, and the successful implementation of the general vaccination plan.

The next is Simulating the behaviour of vaccine-avoiding people. The goal of general vaccination against COVID-19 disease is to control the epidemic that has engulfed the world. Negative publicity for vaccine opponents can challenge public vaccination. Reasons for people avoiding the vaccine are distrust and fear of vaccine side effects, the ineffectiveness of vaccines against coronavirus, false and negative propaganda about infection and death after vaccination of coronavirus in cyberspace, and lack of trust in governments due to the economic aspect of vaccine production. In traditional societies, cultural and religious factors can increase the number of people vaccinated. Therefore, the impact of people's participation in receiving the vaccine on the system is examined under several scenarios. The simulation is performed for $\beta = 0.3$ and $\pi = 0.3, 0.2$ and 0.1. based on the model's parameters, according to Figure 4, the vaccinated population is approximately equal to the vaccination rate of 0.3 and 0.2, approximately equal to the rate of 0.57 and 0.63, respectively.

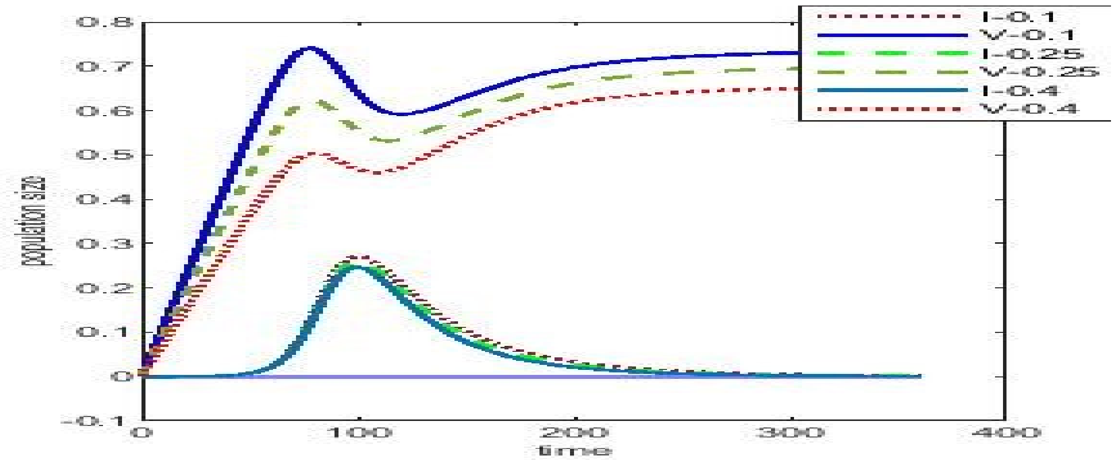


Figure 4. Proportional population I and V for 3 avoidance Vaccine rate

As shown in the figure above, the level of the vaccinated population cannot provide relative safety at the community level. Reducing the avoidance vaccine rate to 0.1 will bring the level of immunity to an optimal level with about 0.74 vaccinated populations. Therefore, observing the health protocols to reduce the disease transmission rate to 0.3 and increasing the awareness rate to reduce the number of vaccine avoiding people will lead to the successful implementation of the general vaccination plan.

In this research, a comprehensive dynamic system based on differential equations was designed, and the effect of the mentioned social behaviours on the system was investigated. Compared to other studies (Usherwood et al., 2021, Li et al., 2021a) and (Poonia et al., 2022), the designed model includes more variables, such as the vaccinated population and asymptomatic patients. In addition, the relationship between behaviour and disease outbreaks has been investigated in several scenarios. With a forward-looking approach, the designed model simulates the outbreak of the disease, and according to the presented results, health managers can make the necessary preparations to face the disease, and policymakers can make appropriate decisions regarding social behaviours.

4. Conclusion

In the world today, The COVID-19 pandemic is one of the most critical issues. Although some countries have controlled the infection, much research is still needed to uncover the complex dynamics of virus transmission. In this paper, a mathematical model for the dynamics of COVID-19 with an emphasis on vaccination was developed. One of the critical problems of some communities in implementing the general vaccination plan to control the virus is non-participation in receiving the vaccine and the existence of a vaccine-avoiding population. Another issue is the feeling of security caused by receiving the vaccine and not following the health protocols. These two behaviours were considered effective parameters of the disease process. Due to the social disruption in following the health instructions, the reduction of social capital and the lack of social trust cause the health instructions to not be tracked. Some people think that they don't get infected and get normal after the vaccine when this isn't the case. The incidence is very low, but it is still possible. Health protocols such as using a mask, observing social distancing, avoiding everyone, and being in closed spaces should also be observed after vaccination. None of these vaccines provides 100% certainty in preventing infection. The simulation results showed that it is not possible to achieve the desired level of safety resulting from vaccine injection without observing health protocols. On the other hand, due to the rate of infection, increasing the rate of participation in receiving vaccines and reducing the population of vaccine vaccines can control the epidemic. Common causes of immunization in people who do not believe in COVID-19 disease believe in the human mind's fabrication; the model of this study focuses on the vaccinated population and the behavioural parameters that affect it. Lack of accurate knowledge about vaccine availability rates, vaccine efficacy and other factors causes some ambiguity. Therefore, although a few predictions from our study are essential, all possible uncertainties must be considered. Due to the appropriate distribution of vaccine injections in Iran, it is assumed that the rate of access to the vaccine and its effectiveness is considered constant. With access to more accurate information, new data can be incorporated directly into our model for more accurate results. Another point is that the infection rate is also assumed to be constant, and the results are shown per peak. It is suggested that the proposed model be implemented according to the vaccinated population and the effects of the possible mutant virus in the next peak on the future of the population and the health care system. We expect informed policy development and successful vaccination to contribute to public health. Presenting the results of the model and the effect of changes in social behaviour and increasing the rate of vaccine injection can cause awareness in the community to reduce the rate of vaccination avoidance and increase compliance with health protocols.

Researchers in management, epidemiology, dynamic systems, and data science can benefit from the suggestions presented in their future research. In the disease process simulation model, it is suggested to make predictions by considering all possible uncertainties. In this study, the vaccination rate is constant during the study period; it is suggested to consider the vaccination rate as a time-dependent function. Simulating the model for different regions and paying attention to the fact that the vaccine access rate varies from one region to another can be considered. Also, the effectiveness of different types of vaccines, the different effects of vaccines against different mutated strains of coronavirus and the population's age groups can help develop the model. Using the artificial intelligence approach to estimate the model's parameters increases the predictions' accuracy. It is suggested that mathematicians discuss the uniqueness of the solution using the existing theorems to prove the stability of the dynamic system.

5. Research limitations

In the dynamic model for predicting the course of the disease, due to the lack of available information, the model's parameters are mainly taken from previous studies and the initial hypothetical values are included in the model. The lack of access to a suitable computer system has made it difficult to implement modelling in a situation closer to reality.

Simulation in compartments modelling has been done for cases where other parameters are constant, and by scenario changing the same parameters entered into the model, the future situation of the epidemic has been predicted if another crisis happens at the same time as the parameters change in the real world research will not be very effective.

In this research, it has been tried to define human factors in the form of mathematical language, and for this case, it is assumed that the parameter values are constant during the simulation period, but human behaviour is very unpredictable.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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