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Agent-based Modeling of COVID-19: A case study of Hyderabad City

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ABSTRACT

This research aims to design and develop an agent-based model (ABM) that can simulate the COVID-19 outbreak, presenting the interaction dynamics and impact of various control strategies imposed in the city of Hyderabad, Pakistan. The observations include how ABM controls the disease outbreak depending on different scenarios. The individuals are visually represented as agents that can interact with each other and make decisions depending on the situation. The observations are made by studying the dynamics of the behavior of individual agents, and their movements from one compartment to the other. The ABM model is developed in NetLogo and simulates various hypothetical scenarios that reflect the real behavior of the virus's interaction with humans and their environment while adjusting medical, social, and demographic parameters. The study results provide details on how restricting the social interactions between individuals and their movement decreases the rate of the spread of the virus.

KEYWORDS

Agent-based modeling system, COVID-19 outbreak, NetLogo, pandemic, SEIR model, simulation.

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INTRODUCTION

On January 30th, 2020, the World Health Organization (WHO) classified the COVID-19 outbreak as the sixth public health of emergency service [1, 2]. Severe acute respiratory syndrome COVID-19 (SARS-CoV-2) has proved to be the worst infectious disease due to different reasons including a high number of people infected, high mortality rate, and highly recorded demand for healthcare resources [3]. This disease was first reported in December 2019 in the City of Wuhan in China [4]. According to the WHO report, the total worldwide COVID-19 confirmed cases have reached 571,198,904 till 25th July 2022, and out of these total confirmed cases, 6,387,863 have resulted in fatalities till date 25th July 2022 [1, 2]. As a result of the COVID-19 epidemic throughout the world, on 26th February 2020 Government of Pakistan's Health ministry confirmed the First COVID-19 case in Pakistan [5, 6]. Until 25th July 2022 Pakistan reached 1,553,325 confirmed positive cases, out of which 30,483 people lost their lives to the disease. Additionally, Sindh Province of Pakistan reported the highest number of positive cases with a total of 590,634 till July 25th, 2022 [6]. As the extent of the threat continues to manifest with new variants and the severity of the disease and its spread pattern becomes clearer day by day, computer simulations have become the best option for governments to rely upon in order to decide how the impact can be reduced at its best, with more importance on how the disease's growth curve can be flattened hence to decrease the burden on the health care organizations. The number of cases in Hyderabad city recorded the 2nd highest after Karachi, therefore understanding how the pandemic's variables operate and change in Hyderabad is crucial.

With little social safety net protection and a context of high unpredictability, Hyderabad has faced the pandemic emergency. By the final week of March 2020, several precautions had been put in place to fight the epidemic, including the closing of schools and colleges, public transit, public events, and workplaces, as well as limits on meetings and domestic and international travel. Since May 2020 the intensity of the applied measures was reduced which poses a certain concern of risk and spread of the disease.

The first wave of the disease ended in mid-July 2020. However, an increase in cases and deaths was noted in November 2020, hence the second wave started and it increased the burden on healthcare resources again. The rate of recovery exceeded the rate of mortality. The ratio, however, varies from nation to nation and area to region. It was observed that the United States of America was the most impacted nation, followed by various regions of Europe [3]. The pandemic in Pakistan has evidenced that 25% of the population is under the poverty line and imposing complete lockdowns is not a feasible option for their survival. A complete lockdown leads to slowing down the global economy.

We are dealing with a multidimensional, complex, and dynamic phenomenon with many variables that interact repeatedly and produce emergent behaviors that are highly uncertain and cannot be predicted from the individual behavior of the variables but rather from their collective behavior. It cannot be met with solutions that are fragmented and operate from linear, disjointed, and reductionist viewpoints, either.

The major goal of this research work is to use agent-based modeling (ABM) and incorporate subjective assumptions to create a model that will help us comprehend the complexity of the pandemic [7]. Through ABM, human agents are created according to the demographic condition in the city of Hyderabad as decision-making entities, where each agent assesses its situation and makes decision-based on the set of rules after applying a Susceptible-Exposed-Infected-Recovered (SEIR) model to simulate the transmission of COVID-19 among them. The proposed model will help the community and Government in taking better decisions to control COVID-19.

The rest of the paper is structured as follows: Section II presents a literature review followed by the material and methods used in this paper. The results and discussion are presented next followed by the conclusion.

LITERATURE REVIEW

COVID-19 is an infectious disease that spreads when a person encounters someone infected with a novel coronavirus. Originated from one of the biggest animal markets in Wuhan, city of China, earlier in 2019, WHO declared COVID-19 public health emergency in January 2020, and later in March 2020, it was declared a pandemic when it started affecting the whole world in a few months becoming one of the biggest threat to the world. This virus caused the whole world to paralyze resulting in months-long lockdowns, and the closure of markets, educational institutions, and offices affecting individual lives around the world. According to WHO statistics, about 210 countries were affected by the virus, marking the affected population counts to 6 million. 300 thousand people lost their lives as stated by WHO statistics. The number of people affected, and the death toll varies from country to country [3].

The spread of COVID-19 highly depends on the interaction and movement of people. To control any future outbreaks of COVID-19 some control strategies are required that can not only help in controlling the spread but also play a vital role in predictions of future outbreaks [7]. Decision-making methods that are being used traditionally generally use opinions from experts to predict the efficiency of a strategy that is being applied. These methods can be used in combination with new modeling techniques to measure the impact of control strategies and predict future conditions. Modeling and simulation of such systems have attracted the attention of scientists and researchers in recent years [7, 10, 11].

Computational modeling techniques and simulations can be used as a robust tools to study the dynamics of complex systems and phenomena. These techniques are also useful to study and predict the control and future behavior of contagious diseases like COVID-19 through spatial analysis due to their flexibility and ability to dynamically analyze the new information that is obtained over time. There are several computational models and simulating techniques that are widely being used to study the behavior and control the spread of COVID-19 in which agent-based modeling or ABM is the most popular and is being used widely by scientists and researchers. Due to its flexibility and bottom-up structure, it helps the decision makers to design strategies by combining time and space [5].

ABM models that analyze the spread of COVID-19 are designed based on a variety of spatial data to develop a system that is close to reality where the movement and interactions of agents that represent humans can be observed efficiently. All other factors including social and economic conditions that can affect the movement of agents from one compartment (see section iv) are considered during the development of the model [5].

ABM and simulation is a new modeling technique that is being used globally to control the spread of the virus by dividing the area into different compartments and studying the dynamics depending on the movement of individuals, their behaviors, and other social and economic factors. ABMs contain autonomous agents that can interact with each other. ABMs are widely being implemented across the globe in a variety of different applications because of computation advances and their potential of making decisions with appropriate reasoning. These applications range from understanding the dynamics of behavior of business organizations, Stock markets, and consumer behavior in consumer markets to understanding and predicting the effects of pandemics like COVID-19 and predicting the factors that were responsible for the destruction of many ancient civilizations [9]. ABM systems are implemented in a variety of different software and programming languages such as NetLogo, Java, and Python. While implementing a system model for ABMs, the programmer defines the system mapping for which ABMS is being implemented, and its categories (i.e., compartments as defined in Section III and Section IV). The programmer also defines its agents and their behavior and rules. These rules define the behavior of an agent in different situations and how they will interact with each other. Modeling of agents can be done on any kind of system ranging from small desktops to large-scale computer systems [9]. Some examples of modeling environments to develop ABM on larger-scale computer systems are Repast toolkit for North, Collier, and Vos [12], and Swarm for SDG [13].

ABM has a key feature of understanding the dynamics and behaviors of complex systems for emergent, adaptive, and non-linear phenomena with the help of simulations. They are considered more practical, adaptive, and communicative as compared to the traditional models that are usually composed of mathematically based theories and natural language. ABM agents are designed to take decisions and predict future behaviors based on past events [14]. Computers are considered a laboratory for the modeling of different systems where their agent's interaction with each other and other behavioral dynamics provides the results from the simulations. In the case of ABM, the model simulates the system to observe the behavior and interactions of agents from the micro-level to the macro-level and provide the result. These models are types of computer programs that are programmed to represent the real world in digital form to derive results based on different scenarios. But this computational approach to model ABM becomes challenging as the model becomes more complex where simulation of each agent consumes more time and effort [14].

The first study to investigate the combined approach incorporating quarantine, school closures, and workplace distancing using simulation was carried out in Singapore [11]. The study proposed control measures to decrease the indigenous transmission rates of COVID-19.

MATERIALS AND METHODS

A. Study Area

Hyderabad city of Pakistan is the 2nd largest city located in the province of Sindh and the 8th largest city in Pakistan. According to the census of 2017 total population of Hyderabad increased from 0.6 million in 1951 to 2.9 million making it a densely populated area with 42000 people living on each km making it a leading city with a high urban population in the world after Bangladesh's Dhaka [15]. This population is still increasing at 100 times from time to time. Hyderabad reported its first COVID-19 case on March 10th, 2019. Although the city's positivity rate decreased between July and August, the rise in cases was seen afterward [16].

According to statistics released on November 20th, 2020, from the district health office (DHO), Hyderabad had 1,355 active coronavirus cases and 1,332 of these patients were being isolated at home. A total of 6,774 positive cases—5,314 of which were recovered—were reported since the outbreak first reached Hyderabad. The district has reported 105 documented deaths. However, this death rate does not include patients who were hospitalized and passed away at the LUH City branch but were originally from other Sindh districts [16].

According to daily status reports released by the provincial government in November 2020, Smart lockdowns were implemented in 70 areas of the city by the district administration in June with the approval of the Sindh government, which caused a decline in the positivity ratio from 38% to 2% in August [16].

B. Investigating Agent-Based Modeling Technique

A variety of different models were proposed to understand the dynamics of the COVID-19 virus globally. This may include understanding its characteristics, ways to control its spread and reduce the risk, and predictions about the number of deaths, hospitalized patients, or other outcomes that may occur during a certain period in an affected area [1]. ABM is defined as a system model that is a collection of various autonomous decision-making entities referred to as Agents. Each agent assesses a situation individually and decides based on a set of rules [9]. The agent may respond to a situation in a variety of different behavioral patterns keeping in view the system it is representing [7]. These behavioral patterns may include consuming, selling, and producing. Each agent may be capable of evolving resulting in unpredicted behavioral patterns emerging. Agents may interact with each other repeatedly, which is a key feature of agent-based modeling techniques which aims to rely on computer systems to explore the dynamics of a problem that is beyond the reach of pure mathematical models. Even a simple agent-based model can provide valuable information and exhibit complex behavioral patterns depending on the system it emulates [1].

ABM systems are widely used in a variety of different fields of science and technology such as computer science, systems science and system dynamics, management sciences, conventional modeling, and simulations [7]. The first agent-based model was used in the 1970s named Sakoda-1971 as the checkerboard model of social interaction [9]. One of the most famous models that got the attention globally during the past few years is SEIR or SIR model. This model divides a large area into small portions (which may refer to as compartments) and defines them under different categories (Suspected, Exposed, Infected, Eliminated, or Recovered) [7] and then applies some mathematical principles to identify the movement of people from one compartment to the other depending on different scenarios like public/social gatherings, public health policies, and other aspects [9].

ABM systems have a variety of different beneficial characteristics. They are flexible systems that can capture emergent phenomena and provide a natural description of a system. By emergent phenomena, we simply refer to a phenomenon that results from the interaction of individual entities [7]. To control the spread of COVID-19, the ABM model simulates the city of Hyderabad as a community and tracks the interaction and spread of the virus between the individuals referred to as agents by keeping track of their movements, their patterns of interactions, other risk factors including the track of public/social gatherings and health policies and SOPs issued by the government [15]. The aim is to propose an agent-based modeling system through simulations to understand and predict the dynamics of the pandemic to concentrate on scenarios that will change over time and configure the conditions to determine such conditions.

C. Investigating Agent

As discussed earlier, an agent-based modeling system divides the COVID-affected area into different groups or compartments. Each compartment is assigned a name depending on the state of infection in that area.

The SEIR model divides the area into 4 categories i.e., Susceptible (S), Exposed (E), Infectious (I), and Recovered (R) [7, 9]. Each of these categories is defined below:

- Susceptible (S): Total population of the area. In the case of Hyderabad, the total population of 2.9 million is susceptible
- Exposed (E): Incubation Period
- Infectious (I): Infected with the COVID virus

- Recovered (R): Recovered or Removed

The flowchart in Fig. 1 illustrates how the SEIR model categorizes the infected area into distinct categories and how control flows from one category to the other. The susceptible category includes people who are likely to counter the disease. When a susceptible person encounters an infected person, he is categorized as Exposed before becoming infected. In case a person catches the infection, he becomes infected and later recovers or dies.

Now, let us consider Hyderabad city as a closed system in Fig. 01, SEIR model. We divide the total population of the city into different categories Susceptible, Exposed, Infected, and Recovered/Removed. During the pandemic, the population of Hyderabad is 2.9 million (see section III). Thus, we can say: S + E + I + R = 2.9 million.

Given a certain number of individuals who are infected with the virus in a given population, let us consider an age group 'n' which represents the mixed pattern of people of a specific age band (each band represents an age category by 10 years) that will change its probability during time 't', when individuals of specific age groups are exposed to the virus. Thus, we can write the equations as:

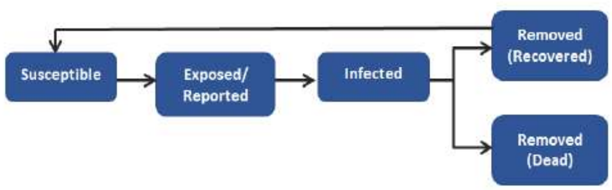

Figure 1. SEIR model structure

$$S_{nt+1} = S_{nt} - \beta S_{nt} \sum_{j=0}^{n} C_{nj}\, I_{jt}^{SC} \quad (1)$$

$$E_{nt+1} = (1-k)E_{nt} + \beta S_{nt} \sum_{j=0}^{n} C_{nj} I_{jt}^{c} + \alpha\beta S_{nt} \sum_{j=0}^{n} C_{nj} I_{jt}^{Sc} \quad (2)$$

$$I_{jt+1} = \rho_n k E_{nt} + (1-\gamma) I_{jt}^{c} \quad (3)$$

$$I_{jt+1} = (1-\rho_n) k E_{nt} + (1-\gamma) I_{jt}^{sc} \quad (4)$$

$$R_{nt+1} = R_{nt} + \gamma I_{jt+1}^{c} + \gamma I_{jt+1}^{Sc} \quad (5)$$

Where *S* represents ratio of suspected individuals, *E* represents ratio of exposed, β represents the transmission rate of the virus, *C* represents the number of interactions between different age groups (*n* and *j* represent two age groups), *I* represent the ratio of infection, *R* represents the ratio of recovery, *(1-ρ)* represents the individuals who do not show symptoms despite being infected, *(1-γ)* represents the rate of recovery. Any individual who is infected with the virus can be checked for being asymptomatic or clinical and can be identified with the help of ρ_n. I^c and I^{sc} represent if the individual is clinical or asymptomatic respectively. The strategies shown by the above equations aim to implement a strategy to decrease social interactions between individuals and slow the spread of the virus.

In the proposed model, different situations were simulated to gather information about the factors that play a major role in the spread of COVID. In the first scenario, it was assumed that the social interaction pattern was not changed. Individuals continue to work as per their normal routines. All educational institutions and offices are open to work. In the second scenario, a partial lockdown was imposed in Hyderabad for 90 days with no restriction on social distancing. The partial lockdown was implemented, the closure of educational institutions only. In the third scenario, a Complete lockdown was imposed for another period of 90 days with the closure of schools, universities, and offices. People started working remotely and all educational activities were conducted through online applications [11, 17].

D. The Environment of ABM

The proposed SEIR model is developed to visualize the dynamics of the spread of COVID-19 in Hyderabad depending on several social and biological factors. The simulation developed using NetLogo represents a virtual world where the map represents Hyderabad city, and the agents show the population of Hyderabad during the COVID-19 pandemic.

Simulation in Fig. 2 helps the user to observe the effect of a pandemic on the population of Hyderabad over time. Each scenario is observed for 90 days. Red dots on the map represent the infected people whereas green dots represent the uninfected people. During the process, the dots may appear and disappear showing the social activities of individuals of different age bands. Users can change the parameter as per need during the simulation with the help of the slider.

RESULTS AND DISCUSSIONS

The results have been presented based on four considered scenarios which vary based on various restrictions including lockdown, social distances, and so on. The restrictions were implemented for 90 days in each scenario. The dynamics of infected individuals by various age groups have been presented by dividing individuals into 10-year age bands with ages ranging from 0 to 80 years [17].

A. First Scenario

In the first scenario, no restriction was applied over 90 days. Considering the number of infected people is 10, Fig. 3 depicts the dynamics of the simulation under the first scenario. Fig. 3 a) shows the results of the overall dynamics where the green line represents people who are not infected, and the red line shows the infected people. The blue line shows the cases that are reported, and the brown line represents the recovered ones. The dynamics of infected individuals by various age groups have been presented in Fig. 3b). We can observe that the likelihood of the disease increases with an increase in a person's age. According to the results, the highest number of people infected with COVID-19 are of age 80 or above. Similarly, the second highest group is aged 70-79 years. The death rate in the city has been depicted in Fig. 3c). According to the results, we can see there are no deaths under the age of 50. However, most people over the age of 50 have not been able to survive with major fatalities occurring in the age group of 70-80 years followed by 70-60 years.

the age group of 70-80 taking up the most affected people, it can be observed that the rate of infection has been reduced to 50% as compared to the first and second scenarios. Also, observing the death rate in Fig. 5 c), we can see a major reduction in the overall number of deaths. As compared to the

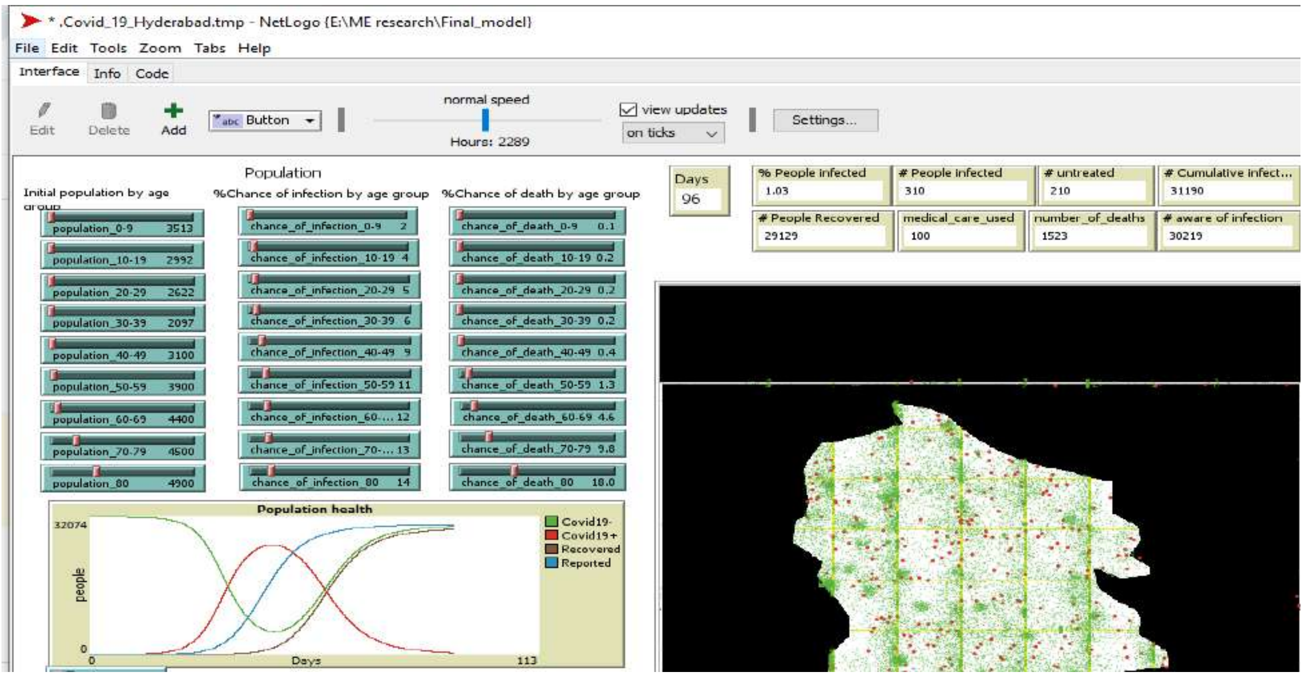

Figure 2. Simulation showing effect of pandemic on populationime

B. Second Scenario

The second scenario represents a situation where a partial lockdown was implemented but without any restriction on social distancing. These restrictions were implemented for 90 days. Fig. 4 presents the dynamics of COVID-19 under the second scenario.

Fig. 4 a) shows the overall dynamics of the second scenario. Fig. 4 b) shows the result of dynamics of infected individuals by various age groups.

As with the first scenario, individuals are divided into groups by 10-year age band with ages ranging from 0 to 80. According to the results, most of the people infected with COVID-19 are from age 50 years to 80 years. The death rate in the city has been depicted in Fig. 4 c). According to the results, most fatalities have occurred in the age group of 70-80 years. Compared to the first scenario, the number of deaths was reduced in this scenario from a maximum of 877 to 823.

C. Third Scenario

The third scenario represents a situation where a partial lockdown was implemented with the restriction of social distancing. Fig. 5 a) shows the dynamics of COVID-19 under the specified circumstances. The current scenario shows variation from the previous two scenarios. Although the individuals affected the most by COVID-19 are still within the age group of 50 years to 80 years as depicted in Fig 5 b). With

first scenario and second scenarios, the number of deaths was reduced to 50% during this time (877 in the first scenario, 823 in the second, and 227 in the third scenario). However, similar to the previous scenarios, most of the people who were not able to survive were above in the age group of 70-80 years.

D. Fourth Scenario

The fourth scenario represents a situation where a complete lockdown was implemented with the restriction of social distancing. According to the results, the number of infected people as compared to the first three scenarios was reduced to 1%. The people infected were mostly between the ages of 40 and above. According to the results, most of the people who were not able to survive were above 80 years of age. As compared to the first scenario and second scenarios, the number of deaths was almost 0% during this time.

DISCUSSION

The results of the proposed SEIR model show the spread of the virus under four different scenarios. These scenarios depicted how COVID-19 would spread if offices and other educational were not closed in Hyderabad city. The average infection rate was determined during 90 days of closure and the non-closure of schools, offices, and other institutions.

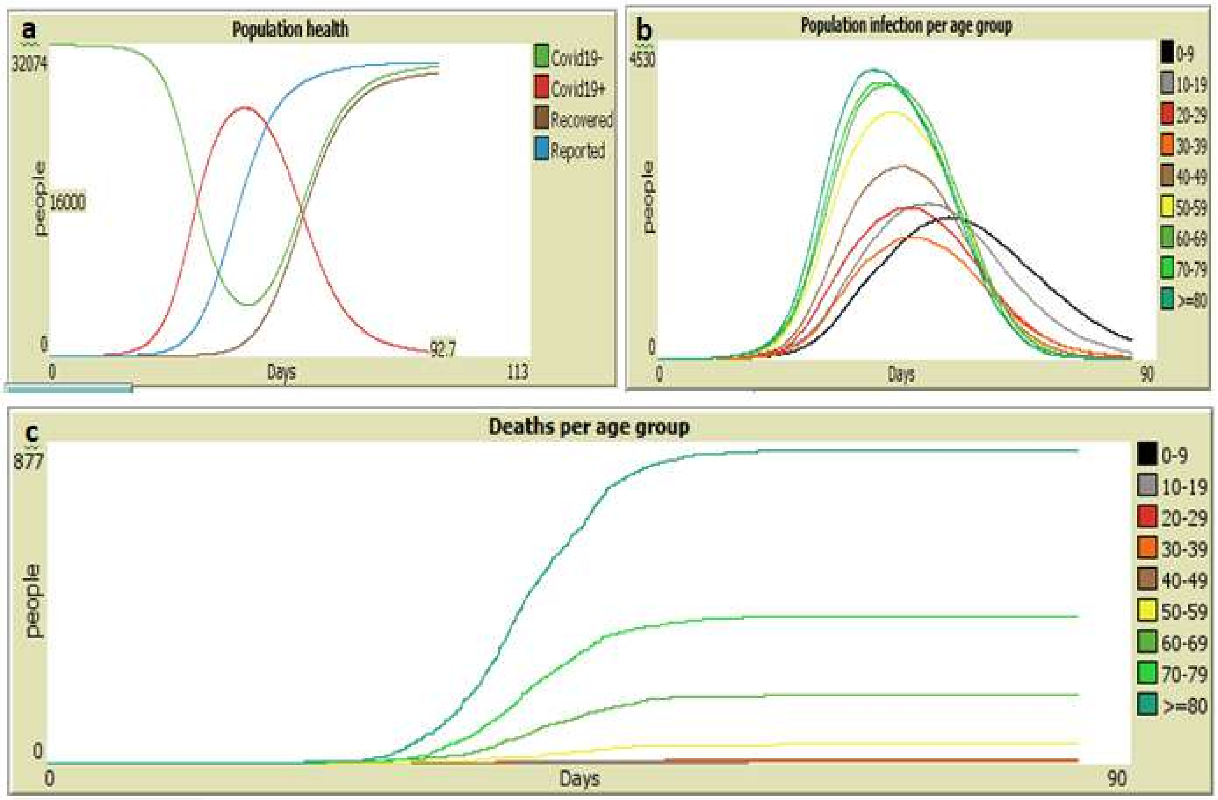

Figure 3. Simulation results of the first scenario – a) Population health, b) population infection per age group, and c) Deaths per age group

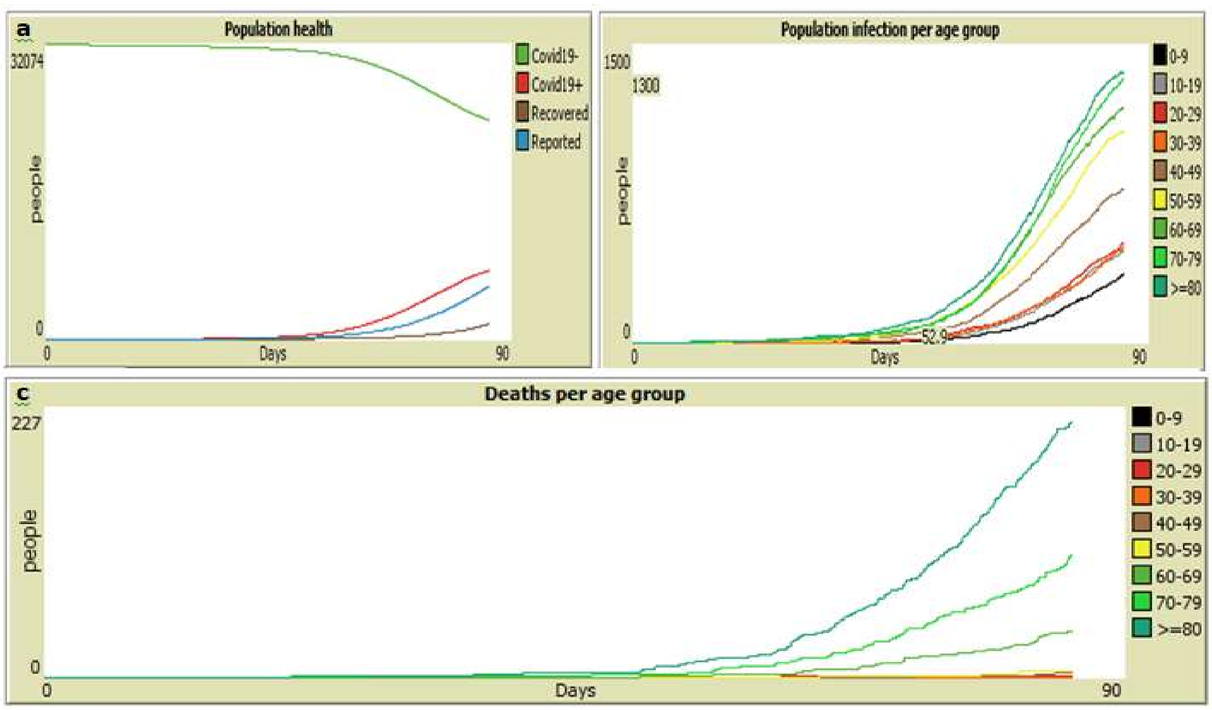

Figure 4. Simulation results of the second scenario: a) population health, b) population infection per age group, and c) Deaths per age groupNew

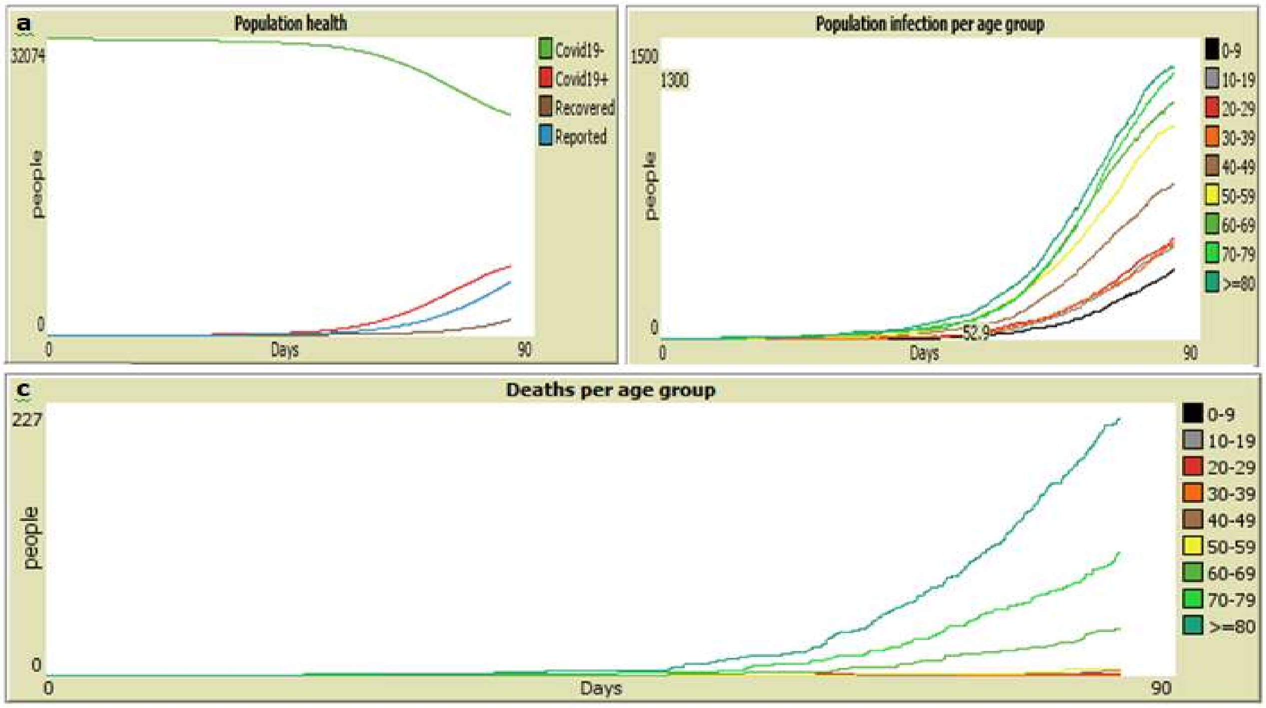

Figure 5. Simulation results of the Third scenario: a) population health, b) population infection per age group, and c) Deaths per age group. N

The results obtained from graphs of the first scenario, where no precautionary measures were taken for 90 days, the COVID-19 infection is seen spreading to 75% of the total population, creating an alarming scenario. If such a scenario is allowed to foster, the lack of planning and resources would overwhelm residents and administrators. There would be a severe shortage of medicines, intensive care medical equipment, ventilators for serious patients, and even a lack of medical personnel. In the second scenario, a partial lockdown was imposed with no restriction on social distancing. The infection percentage was reduced to 50%. Several age groups can be seen as getting infected under this scenario with the highest infection rate falling in the age gap of 70-80 years. In the third scenario, precautionary measures were taken for 90 days in addition to the partial lockdown where people were restricted from attending social gatherings to avoid being exposed to the deadly infection. Under the third scenario, the infection percentage was reduced to 23% further slowing down the spread of the virus and creating a situation where the infected population was able to get good care in hospitals. In the fourth scenario, along with taking precautions, people were forced to quarantine themselves and implement social distancing. This reduced the percentage of infected people to 25%. This scenario considered a lockdown where all educational institutions were closed and the minimum social distance that must be kept was 1.5m. Under such a setting, the death rate was reduced to 1%. The findings of the four scenarios have been summarized in Table 1.

Table 1. Comparison of simulated scenarios

Scenario	Infected population	Highest infection of an infected group	Highest deaths of an infected group	Simulation running Time
First Scenario	Near to 75%	4530 (40 - >80)	877	30 mins 23 sec
Second Scenario	Near to 50%	3010 (50 - >80)	823	33 mins
Third Scenario	Near to 23%	1500 (50 - >80)	227	40 mins 5 sec
Fourth Scenario	Below 1%	10	0	38 mins

In Hyderabad, most of the population is middle, lower middle-class or poor. Majority of the people in the lower middle and poor strata of the city commute from one place to another utilizing the public transportation channel. This mode of travel makes an individual susceptible to the disease. Therefore, proper measures must be taken to ensure the safety of the public, especially individuals of a higher age band because in the worst cases, this may increase the number of people getting hospitalized.

As shown by the results, the main factor behind the spread of COVID-19 is the movement of people and the lack of social distancing. The SEIR model has allowed us to gather more information on the factors that cause the virus to spread rapidly and take proper measures to reduce the spread of the disease. If the educational institutes and offices are closed, it reduces the number of infected people. This strategy can help effectively in reducing the number of people getting exposed and then later catching the virus. The disease outbreak is a complex natural phenomenon. One single model cannot be implemented in the whole world. This is because parameters vary from place to place. The difference in populations, different cultures, literacy rates, general awareness among people, ways of interaction, way of commuting, age, gender, etc. serve as parameters for the modeling purpose that are used to analyze disease dynamics in different parts of the world. For any future research, one must consider these parameters to apply any modeling techniques to design strategies for controlling the spread of COVID-19.

CONCLUSION

It is concluded that simulating the movements of individuals with the implementation of restrictions such as social distancing can highly reduce the number of people at risk. Modeling and simulation of the COVID-19 outbreak in a region as well as investigating the efficiency of control strategies useful in assisting health policymakers and strategy designers to propose a strategy that can help in controlling and preventing the COVID-19 outbreak. This is the main contribution of this research. In this research, the outbreak of COVID-19 was simulated in Hyderabad city with the help of an agent-based model SEIR that had the capability of simulating people's movement with the help of agents. Due to its capability in modeling people's movements as well as their interactions which are two main causes of the COVID-19 spread, it helped a lot in gathering information that was useful to control the spread of the virus. The result of the model indicated that social distancing is the most effective measure to reduce the effect of the disease.

CREDIT AUTHOR STATEMENT

Iqbal Khatoon: Data curation, Software Experimentation, Writing Original draft preparation. **Amirita Dewani**: Conceptualization, Methodology. **Areej Fatimah Meghji**: Visualization, Investigation. **Sania Bhatti**: Supervision, Writing- Reviewing and Editing

COMPLIANCE WITH ETHICAL STANDARDS

It is declared that all authors don't have any conflict of interest. Furthermore, informed consent was obtained from all individual participants included in the study.

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