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Decision-Making Framework for Identifying Regions Vulnerable to Transmission of COVID-19 Pandemic

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Highlights

- Proposed a hybrid fuzzy decision-making framework for the analysis of COVID-19.
- Identified the twenty-five relevant factors and classified them into clusters.
- Ranked the clusters and factors based on their criticality to COVID-19 transmission.
- Cities are ranked based on their vulnerability to COVID-19 transmission.
- Study contributes to the discipline of decision analytics and healthcare risk management.

Decision-Making Framework for Identifying Regions Vulnerable to Transmission of COVID-19 Pandemic

Abstract

At the beginning of 2020, the World Health Organization (WHO) identified an unusual coronavirus and declared the associated COVID-19 disease as a global pandemic. We proposed a novel hybrid fuzzy decision-making framework to identify and analyze these transmission factors and conduct proactive decision-making in this context. We identified thirty factors from the extant literature and classified them into six major clusters (*climate*, *hygiene and safety*, *responsiveness to decision-making*, *social and demographic*, *economic*, and *psychological)* with the help of domain experts. We chose the most relevant twenty-five factors using the Fuzzy Delphi Method (FDM) screening from the initial thirty. We computed the weights of those clusters and their constituting factors and ranked them based on their criticality, applying the Fuzzy Analytic Hierarchy Process (FAHP). We found that the top five factors were *global travel*, *delay in travel restriction*, *close contact*, *social cohesiveness*, and *asymptomatic*. To evaluate our framework, we chose ten different geographically located cities and analyzed their exposure to COVID-19 pandemic by ranking them based on their vulnerability of transmission using Fuzzy Technique for Order of Preference by Similarity To Ideal Solution (FTOPSIS). Our study contributes to the discipline of decision analytics and healthcare risk management during a pandemic through these novel findings. Policymakers and healthcare officials can also benefit from our study by formulating and improving existing preventive measures to mitigate future global pandemics. Finally, we performed a sequence of sensitivity analyses to check for the robustness and generalizability of our proposed hybrid decision-making framework.

Keywords: COVID-19; Epidemic transmission; Fuzzy Decision framework; Fuzzy Delphi; Fuzzy A.H.P.; Fuzzy TOPSIS

1. Introduction

On January 7, 2020, an unusual coronavirus formerly named 2019-nCoV by WHO was identified. Later, on January 30, 2020, WHO declared the 2019-nCoV epidemic as a Public Health Emergency of International Concern[1,]. On February 11, 2020, the International Committee on Taxonomy of Viruses renamed this pathogen as the *Severe Acute Respiratory Syndrome Coronavirus* 2 (SARS-CoV-2) (Gorbalenya et al., 2020), while WHO named the epidemic as COVID-19[2]. Globally, it is found on June 17 2020, from the WHO COVID-19 dashboard that there have been 8,043,487 confirmed cases of COVID-19 and 439,487 deaths [3 4].

Fig. 1 illustrates the stagewise of transmission of the COVID-19 disease. Stage 1 shows that a potentially zoonotic virus caused COVID-19, which was revealed through a preliminary phylogenetic analysis. Stage 2 presents the transmission of COVID-19 from animals to human beings (Ahmad et al., 2020; Li et al., 2020; Rothan et al., 2020). Further, the COVID-19 virus demonstrates an incubation time that ranges from 2 to 14 days (Rothan et al., 2020), and Stage 3 shows that it can transmit among human communities through cough droplets, contaminated hands, or surfaces. Next, Stage 4 shows the outbreak of COVID-19 and its transmission within the community (Tack et al., 2020; Rothan et al., 2020). Stage 5 illustrates that COVID-19 gradually becomes a global pandemic disease with exponential growth in active cases (Harapan et al., 2020).

The emergence of a new virus indicates that understanding transmission patterns and their associated risk factors for infection will be limited at the start of an outbreak (WHO, 2020). A mass of academic literature has explored the epidemiology and transmission of COVID-19 among the infected patients and subsequent prevention amongst their close contacts (Duffey et al., 2020; Lipsitch et al., 2020).

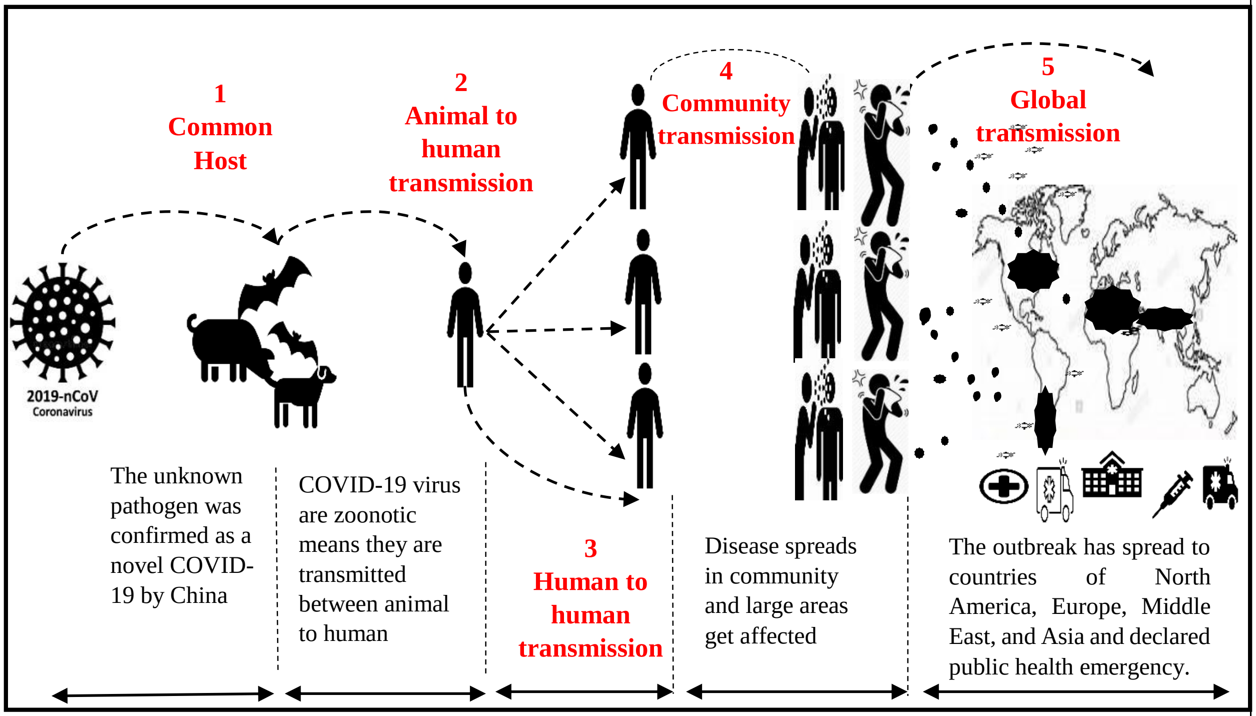

Fig. 1 – Stagewise transmission of the COVID -19

Recently, due to administrative involvements and imposed controls (such as closing the public transportation), and modifications in regular personal hygiene activities (such as, using facemasks at all times, minimizing physical contacts), the cumulative number of confirmed patients has started to decrease (Zhai et al., 2020). However, limited academic literature has explored the factors responsible for the transmission of the COVID-19 disease among the human population across different countries (Harapan et al., 2020).

In this context, many factors are responsible for the COVID-19 transmission disease among human beings. Therefore, policymakers, health officials, and virologists cannot decide the degree of transmission and subsequently plan for mitigation by considering only a few factors. Therefore, there is a requirement for a detailed analysis of the factors responsible for COVID-19 transmission, and all of them should be considered simultaneously to formulate mitigation and preventive strategies by policymakers and health officials. Therefore, Multicriteria decision-making (MCDM) techniques are best applicable (Lakshmi and Suresh, 2020; Maqbool and Khan, 2020; Sangiorgio et al., 2020). In brief, we addressed the following research questions in this study:

- RQ1: What are the critical factors responsible for the transmission of COVID-19 disease?
- RQ2: Among them, which are the most severe and need immediate attention?
- RQ3: Based on these factors, how can policymakers rank different cities & geographical areas vulnerable to COVID-19 transmission?
- RQ4: What can policymakers do to eradicate them and deter the transmission of COVID-19?

To address these research questions, we developed a novel three-phase research framework. In the first phase, we identified and scrutinized the relevant factors for the transmission of COVID-19 using the Fuzzy Delphi Method (FDM). We found that twenty-five factors were relevant out of thirty factors for COVID-19 transmission. After identifying relevant factors of COVID-19 transmission by FDM, in the second phase, we computed the weight of these factors by the Fuzzy Analytic Hierarchy Process (FAHP) method. Subsequently, we ranked them in decreasing order of their severity. In the third phase, we applied a Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (FTOPSIS) method to rank ten cities based on their vulnerabilities of COVID-19 transmission. Also, we checked the consistency of the results with the help of a sensitivity analysis.

The remainder of this paper is structured as follows. In Section 2, we present the factors responsible for the transmission of COVID-19 extracted from the existing literature. In Section 3, we present the research methodology and problem description adopted in this study. We apply our proposed three-phase framework in Section 4, followed by a round of sensitivity analysis. In Section 5, we present the results, discuss the findings, and present the research and policy implications. Finally, in Section 6, we conclude this study and present the future scopes of extension.

2. Literature review

This section presents and discusses the extensive literature regarding the transmission of COVID-19 pandemic, factors responsible for transmitting COVID-19 pandemic, and the problem description.

2.1 Transmission of COVID-19 Pandemic

Since its inception in December 2019, the COVID-19 outbreak has spread across 215 countries and territories (COVID-19 dashboard). As of 1st April 2021, more than 129 million COVID-19 cases and two million deaths were reported (COVID-19 Dashboard: John Hopkins). Throughout the year 2020, the epicenter of the COVID-19 pandemic has continued to shift from China to Europe and then the U.S.A. From Fig 2, we can observe that epicenter of the COVID-19 virus has been moved to India as the second wave hits across the country. Since April 2021, India has been reported approximately 3 lakhs of COVID-19 cases (COVID-19 Dashboard: John Hopkins) daily, which is more precarious and grimmer than the first wave. This escalation in COVID-19 cases is mainly due to the highly contagious double mutant variant of COVID-19, ease of interventions, and negligent behaviour of the people (Xu and Li 2020; Ranjan et al., 2021).

COVID-19 (SARS-CoV-2) has substantially higher infectivity than other coronaviruses, such as SARS-CoV and MERS-CoV, which allows it to transmit rapidly across the world and cause a global pandemic (Chen, 2020). The main route of COVID-19 transmission is human to human through several means, namely droplets, aerosols, and fomites (Wang and Du, 2020; Rathore and Gupta, 2020). In addition, some studies reported that air could be another transmission route of COVID-19 in the form of dust (Qu et al., 2020; Setti et al., 2020; Shao et al., 2021). However, it is a controversial debate among the researchers and scientists on the routes of transmission of COVID-19 pandemic but the whole world following the guidelines of WHO. Therefore, it is important to take precautions like washing hands, rapid isolation of symptomatic patients, social distancing, using masks and sanitizers to avoid exposure to the virus (Coşkun et al., 2021; Li et al., 2021).

Despite all of the precautions mentioned above, all countries worldwide are still affected by this disease, with high levels of infection and mortality rate (Noorimotlagh et al., 2020). Previous literature has identified several factors such as Hygiene and safety (Ghernaout, and Elboughdiri, (2020), Climatic (Jha et al., 2021); Social distancing (Koo et al., 2020; Lewnard and Lo, 2020) and Psychological (Roger et al., 2021) which are responsible for the transmission of COVID-19. Therefore, different prevention and control strategies are needed to implement at the local and global levels. The subsequent development of an efficient and improved strategy is primarily based on identifying the COVID-19 transmission factors. Thus, we explore the existing literature, identify & summarize the possible factors for transmitting the COVID-19 virus. Further, we categorize these factors into six clusters with the help of domain experts, as presented in Table 1. We present a detailed explanation of all factors in the following sub-sections**.**

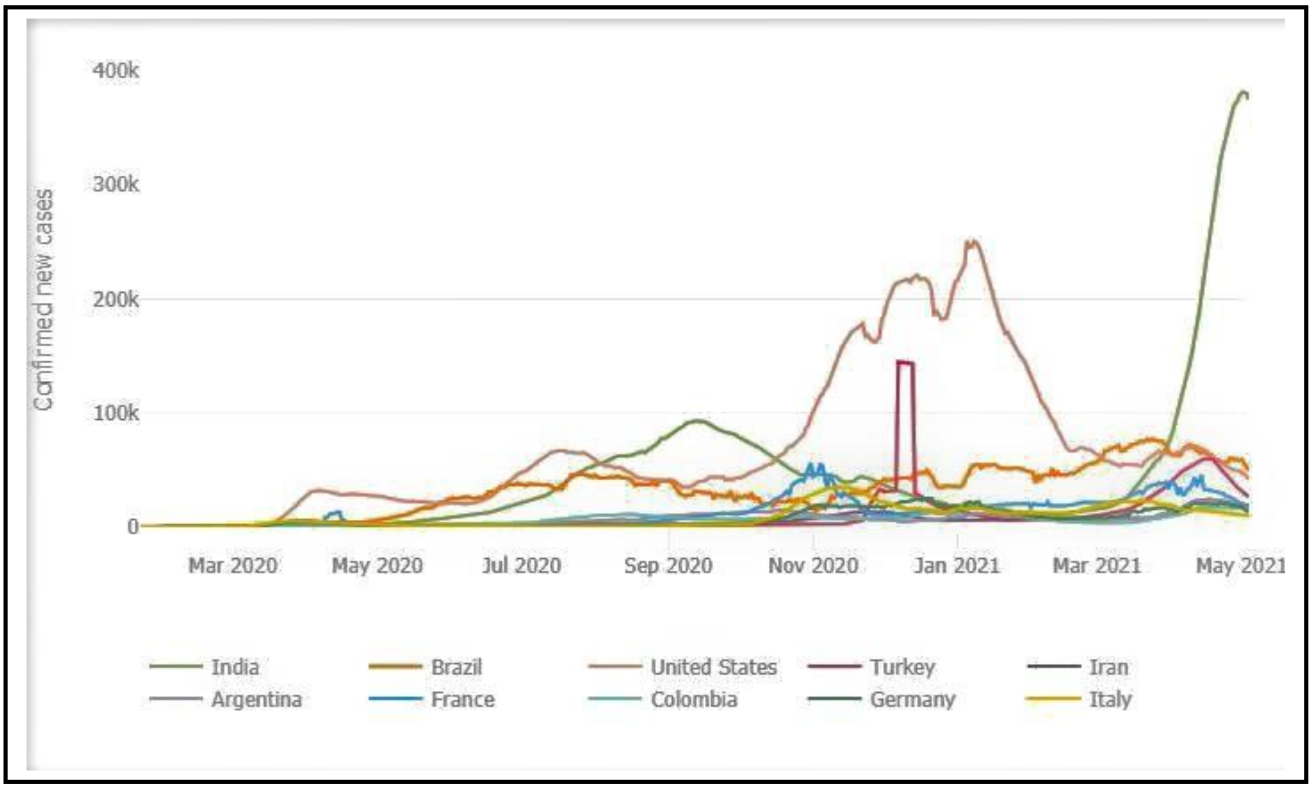

Fig. 2. COVID-19 confirmed new cases in 7-day moving average (Source-Johns Hopkins University)

Table 1: Summary of clusters and their constituting factors with literary sources

Cluster / factor	References
1. **Climatic** ▪ Air quality ▪ Solar radiation ▪ Temperature ▪ Wind speed ▪ Humidity ▪ Rainfall	Ahmadi et al., 2020; Basir et al.,2020; Coccia, 2020; Christopher Flavelle, 2020; Hossain, 2020; Lakshmi Priyadarshini and Suresh, 2020; Qi et al., 2020; Sahin 2020; Wang et al., 2020; Zambrano-Monserrate et al., 2020
2. **Hygiene and Safety** ▪ Hygiene unawareness ▪ Shortage of P.P.E. kit ▪ Spitting ▪ Disposal of medical waste of COVID patient ▪ Close contact ▪ Asymptomatic	Ghernaout and Elboughdiri (2020); Hu et al., 2020; Kachroo, 2020; Singhal., 2020; Sohrabi et al., 2020; Wang et al., 2020; Wu et al., 2020; Vordos et al., 2020
3. **Responsiveness in decisions making** ▪ Quarantine delay ▪ Global mobility ▪ Lack of transparency ▪ Delay in lockdown ▪ Travel restriction ▪ Public misinformation	Aluga, 2020; carl Zimmer, 2020; Chinazzi et al., 2020; Gostin and Wiley, 2020; Kludge et al., 2020; Lau et al., 2020; Nicola et al., 2020; Robin cohen 2020; Sirkeci and Yucesahin, (2020); Sohrabi et al., 2020;
4. **Social and demographic** ▪ Social discrimination ▪ Social cohesiveness (Mass gathering) ▪ Age group ▪ Population density	Ahmed and Memish (2020); Atique and Itumalla (2020); Chang et al., 2020; Charles M Blow, 2020; Chakraborty and Maity, 2020; Chen et al., 2020; John Eligon and Burch, 2020; Fahed et al., 2020; Hossain, 2020; Mat et al., 2020; Mufsin and Muhsin, 2020; Rocklöv and Sjödin,(2020); Reuters, 2020; Van Bavel et al., 2020; Yashoda, 2020;
5. **Economic openness and democracy** ▪ Trade share ▪ Economic openness and democracy ▪ Level of urbanization ▪ Cash and currency	Barua et al., 2020; Chakraborty and Maity, 2020; Hossain, 2020; Jaffe et al., 2020;
6. **Psychological** ▪ Knowledge, attitudes, and practices ▪ Panic buying ▪ Persuasion ▪ Hiding travel history	Ahorsu et al., 2020; Ho et al., 2020; Roy et al., 2020; Van Bavel et al., 2020; Wang et al., 2020; Zhong et al., 2020;

2.2. Factors responsible for the transmission of COVID-19 pandemic

We have explored the existing literature and determined the key factors responsible for the transmission of COVID-19. Findings from the literature show that the climate/ meteorological factors, hygiene and safety, responsiveness, social and, demographic and psychological factors are important for controlling the transmission of COVID-19. Further, we describe these factors in detail through literature synthesis in the following sub-sections.

2.2.1. Climatic factors

Climatic parameters such as temperature, air quality, rainfall, humidity, wind speed, and solar radiation act as catalysts for the rapid transmission of the novel COVID-19 virus (Ahmadi et al., 2020; Bashir et al., 2020; Kulkarni et al., 2021). Chen et al. (2020) found the relationship between the climatic factors and the severity level of COVID-19 transmission and identified that relative humidity, wind speed, and temperature are critical in spreading COVID-19. Wang et al. (2020) have examined the effect of temperature on the transmission of COVID-19 and suggested that low-temperature countries should implement stringent control measures to prevent COVID-19 transmission. ftableThe low-temperature areas between 3-17 degrees Celsius appear to have a relative disadvantage to slow the transmission rate of the COVID-19 virus[5]. Additionally, temperature seasonality in humid continental regions positively influences COVID-19 transmission (Pramanik et al., 2020; Haque & Rahman, 2020; Wei et al., 2020). Studies also find that the relative humidity and diurnal temperature influence the COVID-19 transmission (Islam et al., 2021; Sarkodie & Owusu, 2020; Ozyigit, 2020).

For instance, few studies identified that low humidity might have led to the easy transmission of COVID-19 (Auler et al., 2020; Wang et al., 2020). Liu et al. (2020) studied the effect of humidity on COVID-19 transmission, and their results indicate that low humidity is significantly associated with COVID-19 cases. The high relative humidity (> 95%) is ideal for minimizing the spreading so that the respiratory system can combat the pathogens (Kroumpouzos et al., 2020). A centralized air conditioning (A.C.) system is considered a significant factor in spreading COVID-19 in urban areas because it has a common vent and duct[6]. Therefore, if someone is already infected, then the virus can quickly spread within that particular space. Indian Society of Heating, Refrigerating, and Air Conditioning Engineers (ISHRAE) suggested that air conditioners, coolers, and fans should have an intake of fresh air from outside, which can be achieved by using additional exhaust fans and periodically opening the windows[7].

Adhikari and Yin (2020) explored the relationship between ozone, PM2.5, meteorological variables (i.e. wind speed, temperature, relative humidity, absolute humidity, cloud percentages, and precipitation levels), and COVID-19 transmission rate. Their study's findings showed that the daily average temperature, daily maximum eight-hour ozone concentration, average relative humidity, and cloud percentages were significantly and positively associated with COVID-19 transmission in New York City. Among all these climatic factors, some researchers found the inverse relationship between wind speed and the COVID-19 transmission rate (Ahmadi et al., 2020; Bashir et al., 2020). Hence, the transmission rate is higher in the regions with lower wind speed. In addition to human-to-human transmission, Coccia (2020) revealed that the rate of spreading of COVID-19 could increase due to polluted air. Zambrano-Monserrate et al. (2020) found that regions having a high density of $CO, NO_2,$ $O_3,$ $PM_{2.5},$ and PM_{10} might have high chances of transmission of COVID-19. Hence, the air pollution level and COVID 19 transmission rate have a significant association (Coccia, 2020).

2.2.2. Hygiene and safety factors

Primarily, a person is at a high risk of infection who has been in direct contact with a COVID-19 patient (WHO, 2020). Recent studies indicate that people infected with COVID -19 virus but do not have any symptoms (i.e., asymptomatic) are also responsible for the transmission of the COVID-19 (Hu et al., 2020). Out of the 1723 travellers, 189 asymptomatic people were tested positive for the COVID-19 virus on February 17, 2020 (Moriarty et al., 2020). These asymptomatic patients are challenging to identify, and by the time when they are spotted, they have already infected too many people.

Next, personal protective equipment (P.P.E.)[8] such as masks and face shields help to protect the doctors as well as ordinary people from the COVID-19 patients (Sobel et al., 2020). WHO has already warned about the severe disruption of the global supply of P.P.E. items and recommends the industry and governments to increase production by at least 40%[9] to meet the rising global demand. According to Guo et al. (2020), the COVID-19 disease can widely circulate through the ambient air and surfaces in both the intensive care units (I.C.U.), and a medical ward specified COVID-19, indicating a high potential risk of spreading among the doctors and medical staffs. Thus, a proper and timely supply of P.P.E. is critical to slow down the rate of transmission.

Further, medical waste from the hospitals and homes, such as used gloves, masks, gowns, and tissues, could be a potential transmission route of the contagious COVID-19. Due to this reason, sanitation workers and the rag-pickers are prone to COVID-19 infection from regular handling of unmarked medical waste[10].

2.2.3. Responsiveness in decision-making

Major behavioural interventions have been implemented worldwide to mitigate the spread of COVID-19 (Kraemer, 2020; Zhu, 2020). Countries have announced full travel restrictions (Gössling et al., 2020), lockdowns (Ku et al., 2020), forced quarantines (Piguillem, 2020; Nussbaumer- Streit et al., 2020) to reduce the transmission rate. Lockdown has shown a significant positive impact in curbing COVID-19 transmission and reducing pollution level due to lesser vehicle movement and improved air quality in many Indian cities (Jadhav et al., 2020). On January 23, 2020, China imposed a lockdown, closed all public transports and social activities in Wuhan and Ezhou provinces. After WHO declared COVID-19 as a health emergency globally on January 30, 2020, many countries announced border control measures to prevent tourists with travel history from China. On February 2, 2020, the

Philippines imposed a ban on global travellers arriving from China, Hongkong, Macao and a mandatory 14-day quarantine period (de Bruin et al., 2020). Gondauri and Batiashvili (2020) studied the influence of human travel and mobility on transmitting the COVID-19 virus and found it significant. In addition, quarantine delay and delay in COVID-19 diagnosis have fueled the transmission of COVID-19 (Kahan et al., 2020; Wells et al., 2021; Yang, 2021). Therefore, the governments of countries are legally enforcing quarantines and travel restrictions.

Consequently, policymakers have been gradually serving penalties to people who breached the extremely restrictive ban (de Bruin et al., 2020). In response, various communication media (such as outdoor banners, social media, drones-based warnings) were administered in combination with the punishments. On March 20, 2020, WHO brought a dedicated messaging platform using WhatsApp[11] and Viber[12] in different global languages to transmit accurate information about COVID-19. A similar preventive strategy was introduced in Amsterdam when a citizen had coughed on the face of a police officer on March 27, 2020. Such approaches help to suppress COVID-19 transmission and provide more responsiveness to the incumbent overstretched healthcare systems.

2.2.4. Social and demographic factors

Social and demographic factors mainly consist of *social cohesiveness* (mass gathering), *social discrimination*, *population density*, and *age group* (McCloskey et al., 2020; Gulrandhe et al., 2020). Mass gatherings occur due to various factors, e.g., religious events, panic mobility, the interstate movement of workers, and may lead to faster transmission of COVID-19. For instance, in China, the celebration of the Lunar New Year started at the same time when the COVID-19 outbreak happened. Because it is the most celebrated time of the year, the Lunar New Year leads to huge social gatherings and massive migrations (more than 3 billion trips)[13]. As a result, COVID-19 cases increased at a much higher rate. It was estimated that 5 million people travelled from Wuhan city, the epicenter of COVID-19, to other places of the world (Chen et al., 2020). In another incident, when a large number of pilgrims returned to Pakistan after attending mass prayers in Iran, they were tested COVID-19 positive, and when more than 10,000 pilgrims gathered for prayer in Bangladesh during the COVID-19 crisis[14]. A mass gathering in Kuala Lumpur in February 2020 resulted in more than a hundred new COVID-19 infected cases across Malaysia[15]. Statistics show that more than 35% of the COVID-19 cases in Malaysia directly linked to the Sri Pentatig mass gathering (Mat et al., 2020). In India, approximately 30% of COVID-19 cases were found to be connected to religious mass gatherings[16]. In response, most countries immediately closed places of worship, shopping complexes, offices and cancelled sports tournaments to avoid social gatherings[17]. Therefore, religious tourism and mass religious gatherings are among the key factors for COVID-19 transmission (Mubarak, & Zin, 2020).

Another critical demographic factor for the faster transmission of the COVID-19 virus could be high population density. Researchers found a positive correlation between population density and COVID-19 transmission rate (Selcuk et al., 2021). In India, Mumbai is the worst affected city due to a high population density of 20,634 people/km^2. For instance, the Dharavi slum in Mumbai has a high population density (91,991 people/km^2) and shared access to basic amenities, thereby making these areas extremely vulnerable to the transmission of COVID-19[18] (Kaushal & Mahajan, 2021). Similarly. New York[19] has 28,000 residents /mile^2, and the average increase in cases was around eight times per 100,000, which is higher than any other major city in the U.S., followed by New Jersey[20].

Social stigma and fear of social discrimination among people are also significant factors for COVID-19 transmission. In the context of the COVID-19 outbreak, these factors impact the infected people in society, and others may treat them as outsiders. Such treatment can negatively affect the infected and their caretakers, families, friends, and societies (Samal, 2021; Dalky et al., 2020). In addition, the stigma may indicate that those who are infected get discriminated due to this infectious disease[21] . Fear of social avoidance may lead to physical violence, denials of housing, and future employment of the infected people[22]. Stigma can also make people more likely to hide symptoms or illness, keep them away from getting health care immediately, and prevent individuals from adopting healthy behaviours. This behaviour also means that stigma can make it more difficult to control the transmission of COVID-19. According to a study that includes 211 US counties, the implementation of social distancing norms is the most important factor among population density and wet-bulb daily temperature in reducing COVID-19 transmission (Rubin et al., 2020). Adopting self-protective behaviours (i.e. wearing a mask and social distancing) has effective in reducing individual risk of infection and controlling disease transmission (Papageorge et al., 2021). However, the adoption of social distancing policies (i.e. cancelling events, closing schools and businesses, and issuing stay-at-home orders) have an economically painful impact on society (Adolph et al., 2021; Andersen, 2020; Briscese, 2020; Chiou, 2020).

2.2.5. Economic factors

Country-to-country transmission of the COVID-19 virus mostly depends on the international relations of a country. International trade (e.g., exchange of capital, goods, and services across borders) and economic openness (e.g., non-domestic transactions, imports, and exports) play a vital role in transmitting COVID-19. Higher economic openness and cross-border travel can lead to the easier transmission of COVID-19 (Hossain 2020). An analysis of infected patients from 163 countries shows that lower international trade and less economic openness lead to fewer COVID-19 patients (Hossain, 2020). Jaffe et al. (2020) found that the COVID-19 infections and mortality rates were higher in low-income countries. Such behaviour can be because low-income countries receive a large number of imported goods and international trade visitors.

The exchange of physical currencies is also one of the factors for the faster spread of COVID-19. The US Centers for Disease Control and Prevention (C.D.C.) suggests that COVID-19 can be transmitted through currencies that had direct contact with the infected. Thus, the usage of physical currency can be an easy carrier of COVID-19 among people. A study conducted by New York University (2014) reveals that more than 3000 types of bacteria reside on dollar bills [23]due to the hand-to-hand transfer of the currency. Therefore, industries seek a comprehensive policy for exploring alternative modes of payment (e.g., mobile wallets) to replace physical currency. WHO has issued guidelines regarding the risk of contaminated currency notes and advised consumers to use digital payment methods. In developing countries like India, this issue becomes more critical as most of the population is dependent on physical currencies[24] for business transactions.

Further, people have habits of licking their fingers[25] for easy counting of notes, leading to faster transmission of COVID-19. A study conducted at the Department of Microbiology, Tirunelveli Medical College, Tamil Nadu, India, reports that 86.4%[26] of the 120 currency notes were contaminated with Klebsiella Pneumonia, E-coli, Staphylococcus Aureus. Therefore, policymakers have suggested using alternative currency materials such as polymer currency notes.

2.2.6. Psychological factors

Any pandemic has a psychological effect on human being. Therefore, it is very important to make people aware of them, offer health education and preventive measures to control disease transmission (Johnson and Hariharan, 2017). For instance, Ilesanmi and Alele (2020) studied the effect of knowledge, attitude, and perception of Ebola virus infection among the Nigerian people. Their findings show that most of the people lacked in terms of knowledge and exhibited a negative attitude towards the virus outbreak. Likewise, Roy et al. (2020) surveyed ordinary people to measure their knowledge, attitudes, and practices to cope with the COVID-19 outbreak. Their findings revealed that social distancing, awareness about COVID-19, travel restriction, quarantine, and hygienic measures were essential. Most participants agreed that following these measures and practising a positive attitude could help against the possible infection. However, participants showed fear and apprehension for the inclusion of recovered patients in society. Thus, the fear and anxiety related to highly infectious COVID-19 have influenced people's behaviour in the community. Therefore, adequate awareness among people is needed, which can change their behaviour against recovered patients and avoid social discrimination (Devakumar et al., 2020; He et al., 2020).

2.3 Problem description

COVID-19 is considered a contagious disease and has been declared a pandemic outbreak. The virus had transmitted across many countries, and each of them is implementing preventive measures to reduce the transmission rate. International health agencies such as WHO are frequently releasing advisory reports for taking strict actions on factors responsible for the transmission of COVID-19. Due to this COVID 19 global outbreak, firms witness the disruption in their supply chain and observe the imbalance between demand and supply of goods and services. Furthermore, it becomes challenging for organizations to identify alternative transport and logistic network due to travel restrictions and borders closed. To address the above global health problems, further extensive research is required to identify and analyze the factors responsible for transmitting COVID-19 worldwide.

We developed a hybrid fuzzy decision-making framework for ranking different worldwide geographical cities. Ten different cities, namely, $city$ 1, $city$ 2, $city$ 3, $city$ 4, $city$ 5, $city$ 6, $city$ 7, $city$ 8, $city$ 9, and $city$ 10 were chosen and investigated under twenty-five factors. These twenty-five factors were classified under six different clusters.

In this context, first, we identify these relevant factors using FDM, then we rank them based on their severity using FAHP, and finally assess the vulnerability of COVID-19 transmission in different geographically located cities using FTOPSIS. For the validation of the framework, we performed a sensitivity analysis by varying the weights of the factors. The detailed phase-wise analysis is presented in the next section.

3. Research methodology

In this study, a hybrid fuzzy decision-making framework is developed to identify the critical factors responsible for COVID-19 transmission, and further, this framework is applied to rank the different geographically located cities based on the vulnerability of COVID-19. This fuzzy hybrid framework consists of three phases: FDM, FAHP, and FTOPSIS multicriteria decision-making methods and presented in Fig. 3. This hybrid framework approach is based on fuzzy set theory to analyze our research problem under this uncertain pandemic situation. The methods mentioned above are described in detail in the following sub-sections:

3.1. Fuzzy Delphi Method

The Delphi method was coined by the RAND Corporation (Dalkey and Helmer 1963). It is a qualitative methodology to achieve consensus among a group of experts for identifying and scrutinizing the relevant factors for multicriteria decision-making problems (Hsu et al., 2013; Bouzon et al., 2016; Chen et al., 2018). Although the traditional Delphi method was used to identify the relevant factors, vagueness and uncertainty in the expert opinion persisted (Hsu et al., 2010). Therefore, Fuzzy Set Theory (Zadeh, 1965) was integrated with the Delphi method to overcome the vagueness and subjective nature of human thinking, judgment, and expression (Ishikawa et al., 1993). Cheng and Lin (2002) successfully used the Fuzzy Delphi Method to reach a consensus among the group of experts through triangular fuzzy numbers in military applications. Hence, this study used FDM to identify and scrutinize the factors of COVID-19 transmission. The standard computation procedure for executing the FDM is as follows:

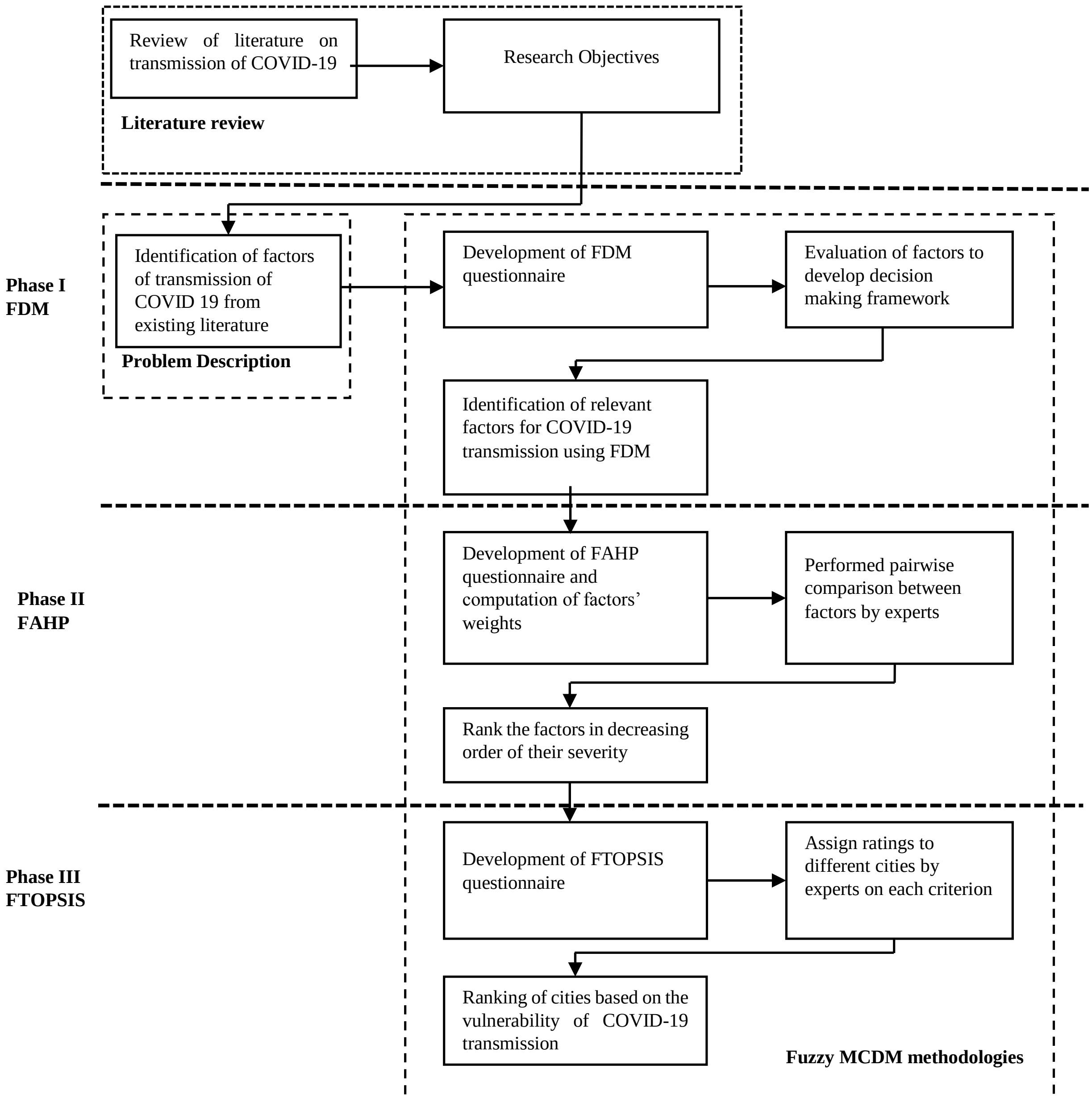

Fig. 3. The flow of research methodology

1. Experts are requested to rate each factor of COVID-19 transmission based on their importance using a linguistic scale, as shown in Table 2. This scale helps to capture the opinions of experts by triangular fuzzy numbers (Ma et al., 2011) and is represented as: $\tilde{\gamma}_i^p = \left(\gamma_{ix}^p, \gamma_{iy}^p, \gamma_{iz}^p\right)$

   where, $\tilde{\gamma}_i^p$ represents the rating of i^{th} factor by p^{th} expert and i represent the total factors, and p represents the total experts.

2. The aggregate rating of each factor is calculated by Geometric Mean Method (Ma et al., 2011; Liu et al., 2020), and the following equation gives it:

$$\tilde{\gamma}_i = (\gamma_{ix}, \gamma_{iy}, \gamma_{iz}) = \left[min_p \, \gamma_{ix}^p \, , (1/\mathrm{P}) \sum_{p=1}^{P} \gamma_{iy}{}^p \, , max_p \gamma_{iz}{}^p \right]$$

where, $\tilde{\gamma}_i$ represents the aggregate rating of i^{th} factor

3. Center of Gravity Method is applied to defuzzify the aggregate rating ($\tilde{\gamma}_i$) with the help of the following formula:

$$\gamma_i = \frac{(\gamma_{ix} + \gamma_{iy} + \gamma_{iz})}{3}$$

where, γ_i represents a crisp score for the aggregate rating of each factor.

4. For identifying the relevant factors, we set a desired value of the threshold α for rejecting and accepting the factor as follows:

If $\gamma_i \geq \alpha$, then factor i is selected

If $\gamma_i < \alpha$, then factor i is rejected

Table 2: Linguistic scales for the FDM (adapted from Singh and Sarkar (2020))

Linguistic terms	Rating	Corresponding fuzzy number
Very important	5	(0.7, 0.9, 0.9)
Important	4	(0.5, 0.7, 0.9)
Moderate	3	(0.3, 0.5, 0.7)
Unimportant	2	(0.1, 0.3, 0.5)
Very Unimportant	1	(0.1, 0.1, 0.3)

3.2. Fuzzy Analytic Hierarchy Process

After identifying relevant factors of COVID-19 transmission by FDM, the weight of each factor is computed by the FAHP method (Chan et al., 2008; Huang et al., 2008). Second, based on the factors' weight, the ranking is done in decreasing order of their severity of transmission of COVID-19. THE traditional A.H.P. method was created by Saaty (1988) and widely used by researchers and decisionmakers to prioritize or rank the factors for multicriteria or multi-factor decision-making problems (Forman and Peniwati 1988; Chan et al., 2019). This method considers the relative importance of factors among themselves to calculate the weights of each criterion and evaluate the different alternatives (Dincer et al., 2016; Awasthi et al., 2018).

The traditional A.H.P. method presents a relatively good approximation when the experts' opinions are consistent (Vaidya and Kumar 2006). However, the expert's opinion is associated with subjectivity & biases, which cannot be treated by the traditional A.H.P. method (Sun et al., 2010). Thus, the FAHP method is applied to incorporate expert's bias & subjectivity, and this method provides more flexibility to experts while comparing one factor with others (Kutlu and Ekmekçioğlu 2012). The necessary steps for calculating the weights of each factor are summarized below:

1. The experts are asked to provide their opinion of paired comparisons using a linguistic scale, as shown in Table 3. A pairwise decision matrix leads to a fuzzy comparison matrix ($\tilde{A}$), as shown in the following equation:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \tilde{a}_{13} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \tilde{a}_{23} & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \tilde{a}_{n3} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \tilde{a}_{13} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \tilde{a}_{23} & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{n2n} & 1/\tilde{a}_{3n} & \cdots & 1 \end{bmatrix}$$

2. The Geometric Mean Method is used to adjust the fuzzy geometric mean for every criterion using the following two equations:

$$\tilde{g}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \dots \dots . \otimes \tilde{a}_{in})^{1/n}$$

$$\widetilde{w}_i = (\tilde{g} \otimes (\tilde{g}_1 \tilde{g}_2 \dots \dots \dots . \tilde{g}_n)^{-1} = (l_i, m_i, n_i)$$

Where, $\tilde{a}_{in}$ is Fuzzy comparison value for each criterion

$\widetilde{w}_i$ is the weight of the criteria in a fuzzy environment

n is number of factors or criteria

i is the number of experts

3. Fuzzy weights are defuzzified by the centre of area (C.O.A.) method (Chou and Chang 2008; Dayanandan and Kalimuthu, 2018) to obtain crisp value by using the below equation:

$$D_i = \frac{l_i + m_i + n_i}{3}$$

Where, D_i= defuzzify value

4. Finally, normalization is performed to estimate the final weights for factors by using the following equation:

$$F_i = \frac{D_i}{\sum_{i=0}^{n} D_i}$$

Where, F_i-s are final weights

Table 3: Linguistic scales for the Fuzzy A.H.P. (adapted from Sun (2010))

Linguistic terms	**Triangular fuzzy number**
Just equal	(1,1,1)
Nearly equal critical	(1,2,3)
Critical one over another	(2,3,4)
Fairly strong critical	(3,4,5)
Strong critical	(4,5,6)
Very strong critical	(5,6,7)
Extremely preferred critical	(6,7,8)
Extreme critical	(7,8,9)
Very extreme critical	(8,9,10)

3.3. Fuzzy Technique for Order of Preference by Similarity to Ideal Solution

After ranking the factors in Phase 2, the FTOPSIS method (Cheng et al., 2002) is applied to rank the cities based on the vulnerability of transmission of COVID-19. Ranking of cities is done by considering all the factors. The traditional TOPSIS method is not appropriate to treat uncertainty and vagueness in the expert's opinion (Kannan et al., 2014), which can be extended using the Fuzzy Set Theory in ambiguous situations (Kuo et al., 2007; Sindhu et al., 2017). For applying the FTOPSIS method, the expert's opinions are collected using the linguistic scales, as shown in Tables 4. The experts rate the alternatives for each criterion. Let us assume, $A = A_1, A_{2,} A_3 \dots \dots A_m$ are the possible alternatives which are evaluated against n criteria ($C = C_1, C_{2,} C_{3 \ldots\ldots} C_n$). The necessary steps of FTOPSIS are briefly given as follows:

1. Fuzzy decision matrix ($\widetilde{D}$) is constructed by the expert's opinion using the linguistic scales, and it is given as:

$$\widetilde{D} = \begin{matrix} \\ A_1 \\ A_2 \\ A_m \\ \\ \end{matrix} \begin{bmatrix} C_1 & C_2 & \ldots & C_n \\ \tilde{X}_{11} & \tilde{X}_{12} & \cdots & \tilde{X}_{1n} \\ \tilde{X}_{21} & \tilde{X}_{22} & \cdots & \tilde{X}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{X}_{m1} & \tilde{X}_{m2} & \cdots & \tilde{X}_{mn} \end{bmatrix}$$

2. Aggregate value or the combined decision of all the experts' fuzzy decision matrix is computed with the following formula:

$$\tilde{X}_{ij} = \frac{1}{P}\left(\tilde{X}_{ij}^1 + \tilde{X}_{ij}^2 + \cdots \tilde{X}_{ij}^p\right) \quad i = 1,2 \ldots.\ m;\ j = 1,2,..n$$

where, $\tilde{X}_{ij}^p$ is the aggregate rating of each alternative for each criterion

3. A fuzzy decision matrix is normalized through a linear scale transformation (Awasthi et al., 2011) to bring the various criteria into a comparable scale as given below:

$$\tilde{R} = [\tilde{r}_{ij}]_{mn}$$

where, $\tilde{R}$ is normalized fuzzy decision matrix and $\tilde{r}_{ij}$ is defined as below:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), and\ c_j^* = max\, c_{ij}\ (Benefit\ criteria)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), and\ a_j^- = min\, a_j^-\ \ (Cost\ criteria)$$

4. A normalized fuzzy decision matrix is multiplied by the weights of each criterion to obtain a weighted normalized matrix ($\tilde{V}$) and is given below:

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mn} \quad i = 1,2 \ldots.\ m;\ j = 1,2,..n$$

where, $\tilde{v}_{ij} = \tilde{r}_{ij}\ .\ w_j$

5. Calculate the fuzzy negative ideal solution (FNIS) denoted by A^- and fuzzy positive ideal solution (FPIS) denoted by A^* for the alternatives and given as follows:

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^- \ldots \tilde{v}_n^-)\ and\ A^* = (\tilde{v}_1^*, \tilde{v}_2^*, .. \tilde{v}_n^*\ )$$

6. The distance (d_i^-, d_i^*) of each alternative from the FNIS (A^-) and FPIS (A^*) is calculated as follows:

$$d_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, v_j^-\right) \qquad i = 1,2,3 \ldots..m$$

$$d_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, v_j^*\right) \qquad i = 1,2,3 \ldots.m$$

7. The closeness coefficient (CC_i) of each alternative is calculated using the below formula:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}, i = 1,2,3 \ldots \ldots m$$

Table 4.1: Linguistic scales for the rating of each city (Sun, 2010)

Linguistic term	Triangular fuzzy number
Very low	(0, 1, 3)
Low	(1, 3, 5)
Medium	(3, 5, 7)
High	(5, 7, 9)
Very high	(7, 9, 10)

Table 4.2: Linguistic scales for the rating of each city across time

Linguistic term	Triangular fuzzy number
Very late	(0, 1, 3)
Late	(1, 3, 5)
Moderate	(3, 5, 7)
Early	(5, 7, 9)
Very early	(7, 9, 10)

4. Application of the proposed framework

4.1 Data collection

In this study, analysis is performed with the help of ten experts from the virologist domain. The virologists having more than ten years of relevant experience were appropriately chosen for our study. The size of the expert panel for this study is acceptable, considering the published articles with nine experts (Hsu et al., 2010), thirteen experts (Ma et al., 2011). These ten experts who were interested in participating in our study were selected and categorized into two different groups: (i) experts who are teaching in the domain(s) of virology (academicians), and (ii) experts who are working as a virologist in laboratories. Experts are requested to draw their judgments on the degree of importance of each responsible factor in the context of disease transmission and are asked to rate them with a fuzzy linguistic scale. The expert's opinion is converted into TFN to achieve relevant factors, weights, and more accurate results and reported in the next section.

4.2 Phase 1: Identification of the relevant factors by FDM

With the help of literature, we collected thirty factors that are responsible for transmitting COVID-19 and, questionnaires were made to include those thirty factors for collecting the expert rating. The questionnaires were sent to ten experts and asked to rate them with a fuzzy linguistic scale (see Table 2). With the help of expert rating, we scrutinize and screen the relevant factors that are mainly responsible for the transmission of COVID-19, whereas the irrelevant factors are rejected. Five factors were rejected, and twenty-five were finalized, as shown in Table 5.

Table 5: Finalizing clusters and their constituting factors that were responsible for the transmission of COVID-19 using Fuzzy Delphi Method

Clusters / Constituting factors	**Fuzzy weights**	**Defuzzification (γ)**	**Decision**
1. Climatic (C)			
Air quality (C_1)	(0.30, 0.63. 0.90)	0.61	Accepted
Solar radiation*	(0.10, 0.45, 0.90)	0.48	**Rejected**
Temperature (C_2)	(0.50, 0.85, 0.90)	0.75	Accepted
Wind speed (C_3)	(0.30, 0.68, 0.90)	0.62	Accepted
Humidity (C_4)	(0.30, 0.68, 0.90)	0.62	Accepted
Rainfall*	(0.10, 0.45, 0.70)	0.40	**Rejected**
2. Hygiene and safety (H)			
Asymptomatic (H_1)	(0.30,0.70 ,0.90)	0.63	Accepted
Shortage of P.P.E. kit (H_2)	(0.30, 0.72, 0.90)	0.64	Accepted
Spitting (H_3)	(0.30, 0.71, 0.90)	0.63	Accepted
Disposal of medical waste of COVID patient (H_4)	(0.30, 0.69, 0.90)	0.63	Accepted

Close contact (H_5)	(0.70, 0.90, 0.90)	0.83	Accepted
Hygiene unawareness (H_6)	(0.50, 0.75, 0.90)	0.71	Accepted
3. Responsiveness in decision making (R)			
Quarantine delay (R_1)	(0.50, 0.79, 0.90)	0.73	Accepted
Global mobility (R_2)	(0.50, 0.85, 0.90)	0.75	Accepted
Lack of transparency*	(0.10, 0.31, 0.70)	0.37	**Rejected**
Delay in lockdown (R_3)	(0.50, 0.75, 0.90)	0.71	Accepted
Delay in travel restriction (R_4)	(0.30, 0.67, 0.90)	0.62	Accepted
Public misinformation*	(0.30, 0.25, 0.70)	0.35	**Rejected**
4. Social and demographic (S)			
Social discrimination (S_1)	(0.30, 0.72, 0.90)	0.64	Accepted
Social cohesiveness (S_2)	(0.50, 0.79, 0.90)	0.73	Accepted
Age group (S_3)	(0.30, 0.69, 0.90)	0.63	Accepted
Population density (S_4)	(0.30, 0.71, 0.90)	0.63	Accepted
5. Economic (E)			
Trade and share (E_1)	(0.30, 0.62, 0.90)	0.60	Accepted
Economic openness and democracy (E_2)	(0.30, 0.63, 0.90)	0.61	Accepted
Level of urbanization*	(0.10, 0.45, 0.70)	0.40	**Rejected**
Cash and currency(E_3)	(0.30, 0.62, 0.90)	0.60	Accepted
6. Psychological (P)			
Knowledge, attitude, Practices (P_1)	(0.30,0.70 ,0.90)	0.63	Accepted
Panic buying (P_2)	(0.30, 0.68, 0.90)	0.62	Accepted
Persuasion (P_3)	(0.30, 0.63. 0.90)	0.61	Accepted
Hiding travel history(P_4)	(0.50, 0.75, 0.90)	0.71	Accepted

*Note: The accepted factor(s) are only coded, and the rejected ones are left uncoded.

4.3 Phase 2: Computation of weights by FAHP

In this phase, we apply the FAHP method to obtain the weights of the clusters and their constituting factors. We constructed the pairwise comparison matrix of the expert's opinion, which was collected with the help of a fuzzy linguistic scale, as shown in Table 3. With the help of this matrix, we calculate the weights of the clusters and their constituting factors of COVID-19 transmission. Table 6 presents the weight of each cluster (W_i) and factor (w_i) under a fuzzy environment using the FAHP method.

Additionally, we ranked the clusters based on their weights and constituting factors based on their global weights, which is calculated by multiplying the factor weight (w_i) with their respective cluster weight (W_i). These rankings are done in decreasing order of their severity.

Table 6: Weight of clusters, constituting factors, and their rankings

S.No	**Cluster**	**Weights (W_i)**	**Rank of cluster**	**Codes**	**Constituting Factor**	**Weights (w_i)**	**Relative ranking**	**Global weight**	**Global ranking**
1.	Climatic (C)	0.04	5	C1	Air quality	0.03	4	0.0014	24
				C2	Temperature	0.62	1	0.0246	11
				C3	Wind speed	0.10	3	0.0039	22
				C4	Humidity	0.25	2	0.0101	17
2.	Hygiene and safety (H)	0.27	2	H1	Asymptomatic	0.27	2	0.0717	5
				H2	Shortage of PPE kit	0.14	3	0.0386	8
				H3	Spitting	0.02	6	0.0051	19
				H4	Disposal of medical waste of COVID patient	0.08	4	0.0219	12
				H5	Close contact	0.44	1	0.1191	3
				H6	Hygiene unawareness	0.04	5	0.0114	16
3.	**Responsiveness to decision making (R)**	0.44	1	R1	Quarantine delay	0.11	3	0.0497	6
				R2	**Global travel**	0.57	1	0.2518	**1**
				R3	Delay in lockdown	0.04	4	0.0161	13
				R4	Delay in travel restriction	0.29	2	0.1271	2
4.	Social and Demographic (S)	0.14	3	S1	Social discrimination	0.04	4	0.0050	21
				S2	Social cohesiveness	0.61	1	0.0858	4
				S3	Age group	0.10	3	0.0141	14
				S4	Population density	0.25	2	0.0351	9
5.	Economic (E)	0.02	6	E1	Trade share	0.25	2	0.0050	20
				E2	Economic openness and democracy	0.69	1	0.0137	15
				E3	Cash and currency	0.07	3	0.0013	25
6.	Psychological (P)	0.08	4	P1	Knowledge, attitudes, and practices	0.12	2	0.0093	18
				P2	Panic buying	0.54	1	0.0429	7
				P3	Persuasion	0.04	4	0.0030	23
				P4	Hiding travel history	0.31	3	0.0248	10

4.4. Phase 3: Ranking of cities based on the vulnerability of COVID-19 transmission using FTOPSIS

This phase deals with the ranking of the chosen ten cities for the implementation of prevention and control strategies. Here, we applied the FTOPSIS method to identify a critical city after calculating the weights of the clusters and their constituting factors from Phase 2. Initially, the fuzzy decision matrix is constructed with the help of two fuzzy linguistic scales for the severity rating of cities (see Table 4). After this step, the fuzzy decision matrix is transformed into a fuzzy normalized decision matrix. Then, the fuzzy normalized decision matrix is multiplied with the weight of each factor for constructing a fuzzy weighted matrix.

Next, the FPIS (A^*) and FNIS (A^-) for each city are calculated. The distance (d^*, d^-) from the FPIS (A^*) and FNIS (A^-) for each city are computed respectively, as shown in Table 7. With the help of these distances, the closeness coefficient (CC_i) for each city is calculated. Finally, cities are ranked based on their closeness coefficient in the decreasing order of their vulnerability of COVID-19 transmission and presented in Table 8.

Table 7: The distance measure between P.I.S. and N.I.S. for each City

Cities/ Criteria	d^*										$d-$									
	$City1$	$City2$	$City3$	$City4$	$City5$	$City6$	$City7$	$City8$	$City9$	$City10$	$City1$	$City2$	$City3$	$City4$	$City5$	$City6$	$City7$	$City8$	$City9$	$City10$
Global travel	0.10	0.11	0.07	0.09	0.06	0.08	0.09	0.08	0.10	0.10	0.03	0.01	0.09	0.04	0.07	0.05	0.07	0.05	0.01	0.03
Delay in travel restriction	0.01	0.03	0.17	0.17	0.16	0.04	0.17	0.17	0.17	0.06	0.13	0.02	0.13	0.13	0.13	0.00	0.13	0.13	0.13	0.02
Close contact	0.11	0.06	0.06	0.08	0.12	0.12	0.01	0.05	0.12	0.11	0.04	0.07	0.07	0.05	0.03	0.03	0.12	0.09	0.02	0.04
Social cohesiveness	0.08	0.09	0.07	0.07	0.15	0.07	0.08	0.09	0.07	0.04	0.07	0.07	0.08	0.07	0.01	0.09	0.07	0.07	0.08	0.14
Asymptomatic	0.08	0.03	0.06	0.05	0.06	0.05	0.02	0.07	0.02	0.06	0.01	0.06	0.04	0.06	0.03	0.05	0.08	0.03	0.08	0.04
Quarantine delay	0.04	0.04	0.01	0.03	0.03	0.01	0.02	0.00	0.01	0.02	0.01	0.01	0.04	0.03	0.02	0.03	0.03	0.04	0.04	0.03
Panic buying	0.17	0.06	0.14	0.07	0.14	0.15	0.01	0.13	0.04	0.17	0.03	0.12	0.04	0.11	0.03	0.03	0.17	0.06	0.16	0.03
Shortage of PPE kit	0.01	0.02	0.02	0.04	0.03	0.01	0.02	0.02	0.03	0.03	0.03	0.04	0.03	0.00	0.02	0.03	0.02	0.03	0.02	0.02
Population density	0.08	0.06	0.10	0.01	0.08	0.08	0.07	0.08	0.06	0.06	0.04	0.06	0.03	0.10	0.04	0.04	0.04	0.05	0.07	0.06
Hiding travel history	0.05	0.09	0.03	0.05	0.04	0.06	0.08	0.02	0.03	0.08	0.04	0.02	0.08	0.04	0.07	0.04	0.03	0.08	0.08	0.03
Temperature	0.02	0.02	0.24	0.29	0.00	0.24	0.01	0.02	0.24	0.02	0.28	0.28	0.05	0.00	0.29	0.05	0.28	0.28	0.05	0.28
Disposal of medical waste of COVID patient	0.03	0.02	0.01	0.00	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.03	0.01	0.02	0.02	0.02	0.03	0.01
Delay in lockdown	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Age group	0.04	0.02	0.01	0.04	0.01	0.04	0.03	0.03	0.04	0.01	0.01	0.03	0.04	0.01	0.04	0.01	0.02	0.03	0.00	0.03
Economic openness and democracy	0.24	0.09	0.17	0.13	0.17	0.09	0.09	0.10	0.15	0.03	0.04	0.21	0.11	0.22	0.11	0.21	0.22	0.18	0.19	0.24
Hygiene unawareness	0.01	0.02	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Humidity	0.01	0.01	0.10	0.01	0.01	0.01	0.01	0.02	0.00	0.01	0.10	0.10	0.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10

Knowledge, attitude, practices	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.01	0.01	0.01	0.05	0.05	0.05	0.00	0.05	0.05	0.05	0.05	0.05	0.05
Spitting	0.01	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00
Trade and share	0.03	0.04	0.05	0.04	0.04	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.03	0.03	0.04	0.03	0.02	0.03	.03	0.04
Social discrimination	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.01
Wind speed	0.03	0.03	0.01	0.01	0.03	0.02	0.03	0.01	0.02	0.02	0.01	0.01	0.02	0.03	0.01	0.02	0.01	0.02	0.03	0.02
Persuasion	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Air quality	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.01	0.01
Cash and currency	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01

Table 8: Closeness coefficient (CC_i) of the cities and ranking

City	d_i^*	d_i^-	$CC_i = \frac{d_i^-}{(d_i^- + d_i^*)}$	***Rank***
City 1	1.20	1.04	0.46	8
City 2	0.87	1.26	0.59	2
City 3	1.38	1.00	0.42	10
City 4	1.28	1.15	0.47	7
City 5	1.19	1.17	0.50	5
City 6	1.20	0.93	0.43	9
City 7	**0.84**	**1.55**	**0.65**	**1**
City 8	1.00	1.42	0.59	3
City 9	1.23	1.21	0.50	6
City 10	0.92	1.28	0.58	4

4.5. Sensitivity analysis

It is important to perform a sensitivity analysis for testing the robustness of the proposed framework under different criterion weights (Patil and Kant, 2014). This analysis implies how the alterations in the weight of factors can influence the ranking of cities by taking each experiment separately. For our sensitivity analysis, a total of thirty experiments are conducted. For each experiment, the closeness coefficient of each city (CC_i) is calculated and presented, as shown in Fig. 4. The original experiment is performed under the actual weights that were obtained from the FAHP method under Phase 2, while thirty experiments are performed by changing the weights of each factor.

The objective of the sensitivity analysis is to identify the most vulnerable city which influences our decision-making process. From Fig 4, we can observe that City7 has the highest closeness coefficient value in nineteen out of thirty experiments. Therefore, among the ten chosen cities, City7 is identified as the most vulnerable for the rapid transmission of COVID-19. Hence, policymakers need to focus on City7 for immediate prevention and control of COVID-19 transmission.

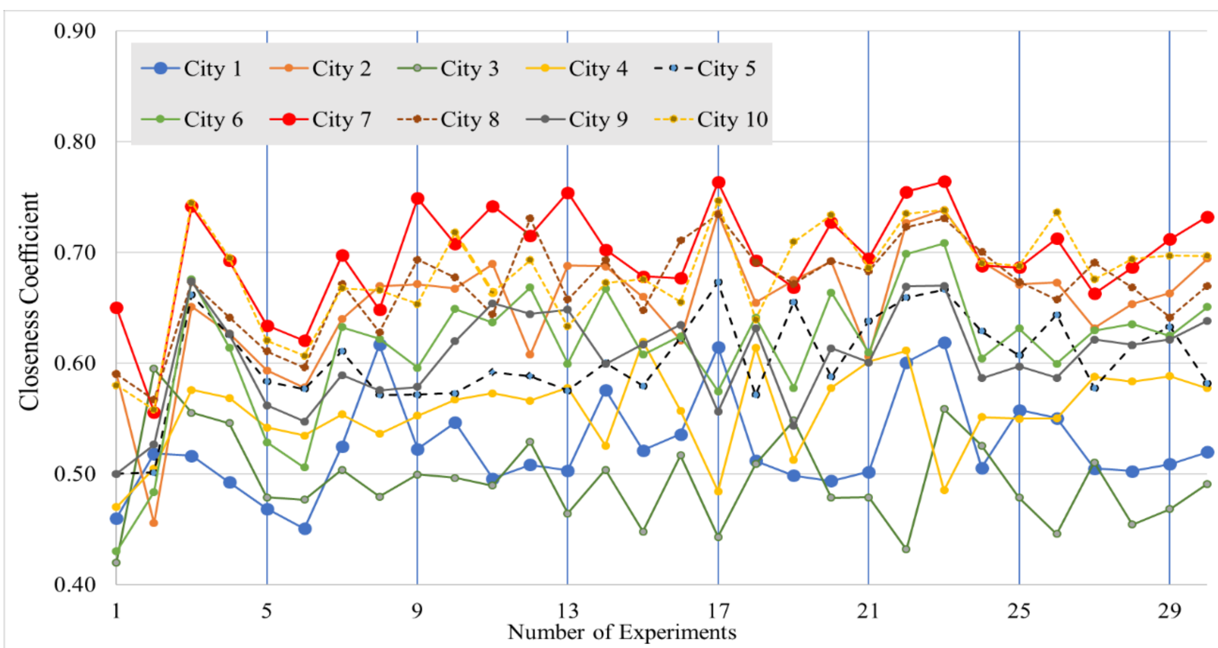

Fig. 4 - Sensitivity analysis experiments demonstrating the variations in the closeness coefficient

4.6. Comparative analysis

From the extant literature, we identified some extensions of fuzzy sets which are applied to analyze the MCDM problems (Liu and Wang, 2007; Oztaysi et al., 2017; Karasan et al., 2018; Mathew et al., 2020). For instance; Dogan et al., (2020) developed decision model for implementing autonomous vehicles as a public transport vehicle by integrating AHP with the Intuitionistic Fuzzy Sets (IFS) and Karasan et al., (2018) ranked the production strategies of a manufacturing plant through integrating AHP and TOPSIS with the IFS. Similarly, Kiracı and Akan, (2020) selected appropriate aircraft for gaining competitive advantage by using hybrid MCDM technique such as interval Type-2 FAHP and interval Type-2 TOPSIS.

Therefore, In this section, we presented a comparative analysis of our problem by integrating two extensions of fuzzy sets namely; Interval Type-2 Fuzzy Set (IT2FS) and IFS with AHP and TOPSIS and it is presented in the Table 9 and Table 10. This comparative analysis helps to understand the variation in the criteria weights and city ranking obtained from these extensions of fuzzy sets.

From the table 9, we can observe that *responsiveness to decision-making* and *Hygiene & safety* clusters have the highest and second highest weight respectively for all the three Fuzzy Sets (FS). If we observe the other clusters' weight, *Social and Demographic* cluster is ranked third in terms of weight for OFS while it is ranked fifth for other two FS. *Psychological* cluster is ranked fourth for all the three FS. *Climatic* cluster is ranked fifth for OFS while it is ranked third for IFS and interval type-2 FS. The *Economic* cluster has the lowest weight for all the three FS.

If we observe the constituting factors weight for their respective cluster, we find the slight change in the ranking of factors based on their weights. For *climatic* cluster, *temperature* factor has the highest weight for all the three FS while *air quality* and *wind speed* have the lowest weight for OFS and other two FS respectively. For *Hygiene and safety* cluster, *Close contact* factor have the highest weight for all the three FS while *Disposal of medical waste of COVID patient* factor and *Spitting* factor have the lowest weight for IFS and other two FS respectively. For *responsiveness to decision-making* cluster, *Global travel* factor has the highest weight for all the three FS while *Delay in lockdown* and *Delay in travel restriction* have the lowest weight for OFS and other two FS respectively. For *responsiveness to decision-making* cluster, *Global travel* factor has the highest weight for all the three FS while *Delay in lockdown* and *Delay in travel restriction* have the lowest weight for OFS and other two FS respectively. Similarly, for *Social and Demographic* cluster, *Social cohesiveness* factor acquires highest weight under all three considered FS while *Social discrimination* has lowest weight for all three FS. In the *Economic* cluster*, Economic openness and democracy* obtains highest weight for all three FS while *trade and share* has lowest weight under IFS and interval type 2 FS. For *Psychological* cluster, *Panic buying* obtains highest weight under all three FS while *Persuasion* has lowest weight for all the three FS.

Table 9: Comparison of weights and ranking by using different fuzzy sets

S.No	**Cluster**	**Cluster Weights (W_i)**			**Codes**	**Constituting Factor**	**Factor Weights**		
		OFS	**IFS**	**Interval type- 2 FS**			**OFS**	**IFS**	**Interval type-2 FS**
1.	Climatic (C)	0.04	0.157	0.178	C1	Air quality	0.03	0.194	0.118
					C2	Temperature	0.62	0.572	0.478
					C3	Wind speed	0.1	0.018	0.058
					C4	Humidity	0.25	0.216	0.346
2.	Hygiene and safety (H)	0.27	0.232	0.194	H1	Asymptomatic	0.27	0.138	0.128
					H2	Shortage of PPE kit	0.14	0.116	0.112
					H3	Spitting	0.02	0.087	0.064
					H4	Disposal of medical waste of COVID patient	0.08	0.053	0.094
					H5	Close contact	0.44	0.514	0.495
					H6	Hygiene unawareness	0.04	0.092	0.107
3.	**Responsiveness to decision making (R)**	0.44	0.384	0.323	R1	Quarantine delay	0.11	0.264	0.238
					R2	**Global travel**	0.57	0.416	0.474
					R3	Delay in lockdown	0.04	0.183	0.176

					R4	Delay in travel restriction	0.29	0.137	0.112
4.	Social and Demographic (S)	0.14	0.087	0.097	S1	Social discrimination	0.04	0.056	0.05
					S2	Social cohesiveness	0.61	0.524	0.584
					S3	Age group	0.1	0.138	0.148
					S4	Population density	0.25	0.282	0.218
5.	Economic (E)	0.03	0.046	0.084	E1	Trade share	0.25	0.134	0.136
					E2	Economic openness and democracy	0.69	0.714	0.578
					E3	Cash and currency	0.07	0.152	0.286
6.	Psychological (P)	0.08	0.094	0.124	P1	Knowledge, attitudes, and practices	0.12	0.075	0.085
					P2	Panic buying	0.54	0.621	0.572
					P3	Persuasion	0.04	0.06	0.069
					P4	Hiding travel history	0.31	0.244	0.274
FS-Fuzzy Set; OFS- Ordinary Fuzzy Set; IFS- Intuitionistic Fuzzy Sets									

In the similar manner, we performed a comparative analysis for the ranking of cities also based on the vulnerability of COVID-19 transmission under all three considered FS. Table 10 presents the ranking of ten different cities under three FS. From this table, we can observe that there is a slightly variation in the ranking of cities for all three FS. City 7 is still most vulnerable for COVID-19 transmission for the all three FS. But City 2 is second most vulnerable for COVID-19 transmission for OFS and interval type-2 FS while it is ranked third most vulnerable city for COVID-19 transmission under IFS. Similarly, we further observe that city 3 is least vulnerable for COVID-19 transmission under OFS while City 6 is least vulnerable for COVID-19 transmission under IFS and interval type-2 FS.

Table 10: Comparsion of cities ranking by using different fuzzy sets

City	***Rank***		
	OFS	**IFS**	**Interval type-2 FS**
City 1	8	8	8
City 2	2	3	2
City 3	10	9	9
City 4	7	7	7
City 5	5	4	5

City 6	9	10	10
City 7	**1**	**1**	**1**
City 8	3	2	3
City 9	6	6	6
City 10	4	5	4
OFS- Ordinary Fuzzy Set; IFS- Intuitionistic Fuzzy Sets			

5. Results and Discussion

Using our proposed three-phase framework, we identified the relevant factors of COVID-19 transmission from the six clusters, determined their weights, subsequent rankings, and finally employed them to identify the most vulnerable among the ten different geographically located cities. This structured three-phase framework (see Fig. 2) would be helpful for the policymakers to implement prevention and control strategies. Initially, thirty factors were identified from the literature, news items, and reputed magazine articles. Further, they were categorized into six main clusters, namely: *climatic (C), hygiene and safety (H), responsiveness to decision-making (R), social and demographic (S), economic (E), and psychological (P).* All the factors are presented in Table 5.

In the first phase, out of the above thirty, five factors are rejected, and twenty-five were finalized based on the expert's ratings using FDM. These five factors which are considered irrelevant for the transmission of COVID-19 are *solar radiation*, *rainfall*, *lack of transparency*, *public misinformation*, and *level of urbanization*.

In the second phase, paired comparisons among the factors are performed to compute the weights using FAHP. From Table 6, we note that *responsiveness to decision-making* has the highest weight among the six clusters and is considered a critical criterion for the transmission of COVID-19. It is followed by *hygiene and safety*, *social and demographic*, *psychological*, *climatic*, and *economic*. Table 6 subsequently presents the weight of the constituting factors within each cluster.

Under the *responsiveness to decision-making (R)* cluster, *global travel* is the most significant factor for the transmission of COVID-19, followed by *delay in travel restriction*, *quarantine delay*, and *delay in lockdown*. On February 28, 2020, the WHO release a travel advisory report to impose a travel ban and lockdown due to the COVID19 outbreak[27]. On March 23, 2020, the U.K. prime minister Boris Johnson announced the implementation of lockdown[28] and, after a month, imposed 14 days mandatory quarantine[29] on international travellers to prevent the risk of imported cases of COVID-19.

Under the *hygiene and safety (H)* cluster, *close contact* is the most significant factor for the transmission of COVID-19, followed by *asymptomatic*, *shortage of P.P.E. kit*, *disposal of medical waste of COVID patient*, *hygiene unawareness*, and *spitting*. Bi et al. (2020) suggested that the transmission rate of COVID-19 can be controlled by avoiding close contact with people. In the first preventive and precautionary report by WHO[30], *close contact* was considered as a primary contributory agent for spreading the COVID-19. Recently, WHO designed the GoData[31] software application with the partners of the global outbreak alert and response network to trace the contact, those who came in contact with COVID-19 patients in the last two weeks.

Under the *social and demographic (S)* cluster, *social cohesiveness* is the most significant factor for the transmission of COVID-19, followed by *population density*, *age group*, and *social discrimination*. Therefore, Anderson et al. (2020) have been drawing attention to the importance of preventive measures such as social distancing in combination with the ban of social cohesiveness (mass gathering), and these measures would have to reduce the transmission rate by about 60% or lesser.

Under the *psychological (P)* cluster, *panic-buying* is the most significant factor for the transmission of COVID-19, followed by *hiding travel history, knowledge, attitudes, and practices,* and *persuasion*. In many countries, it is observed that widespread fear of imposed measures such as forced quarantine and lockdown led to the unpredicted displays of panic buying of goods by the general public (Chew et al., 2020). U.K. was the first country that distributed free food boxes[32] containing essential supplies to vulnerable people for avoiding the rush at the supermarket, which may have resulted in a rise in COVID-19 cases.

Under the *climatic (C)* cluster, the *temperature* is the most significant factor for the transmission of COVID-19, followed by *humidity*, *wind speed*, and *air quality*. Many scientists[33] highlighted that droplets containing virus particles could stay for a more extended period at low temperature, increasing the rate of transmission of COVID-19 between people who come into contact with unclean surfaces. A recent research study has also reported that temperature is significantly associated with the transmission of COVID-19 (Qi et al., 2020).

Under the *economic (E)* cluster, *economic openness and democracy* is the most significant factor for the transmission of COVID-19, followed by trade *share*, and *usage of cash and currency*. Thus, the global pandemic outbreak has resulted in fear and highlighted the downsides of extensive international integration due to governmental restrictions on global trade and the hypermobility of global business travellers. As a result, most of the governments in the world have imposed full travel bans, additional visa requirements, and export restrictions to control the spread of infectious disease[34].

In the third phase, we applied the FTOPSIS method to rank the ten cities to decrease their vulnerability to COVID-19 transmission. This ranking was prepared based on the closeness coefficients, as shown in Table 8. The results show that **City 7** is the most vulnerable city for COVID-19 transmission, and therefore, immediate preventive action is required for reducing the transmission rate. The overall ranking of the cities in the decreasing order of their COVID-19 transmission vulnerabilities is given as follows:

$$\boldsymbol{City\ 7 > City\ 2 > City\ 8 > City\ 10 > City\ 5 > City\ 9 > City\ 4 > City\ 1 > City\ 6 > City\ 3}$$

From the sensitivity analysis results, we observe that $City$ 7 remains the most vulnerable for COVID-19 transmission across 19 out of 30 experiments. Among others, $City$ 2, $City$ 8, $City$ 10, and $City$ 5 retain the second, third, fourth, and fifth ranks based on the closeness coefficient in 22 out of 30 experiments. Therefore, they can be considered among the top five most vulnerable cities facing severe COVID-19 transmission.

5.1 Research implications

Extant literature on COVID-19 shows that a mass of research studies have investigated the propagation, epidemics of the disease diffusion but have ignored a critical examination of the factors responsible for the transmission of COVID-19 in cities and urban areas, followed by the ranking of those cities according to the vulnerability of the transmission of the disease. Furthermore, none of the studies focused on considering most of the critical factors in a single research and developing a decision-making framework to analyze the transmission vulnerability in different urban areas and cities. In this manner, we developed a novel three-phase decision-making framework to address the current research gap.

Our study contributes to the application of Fuzzy Set Theory (Zadeh, 1965) in the context of pandemics and public healthcare management. Due to the different factors responsible for COVID-19 transmission, i.e., economic, cultural, climatic, demographic, and psychological challenges, a lot of uncertainty and vagueness exists among the respondents (Kannan et al., 2014). Fuzzy Set Theory helps to address this issue of the vague and subjective nature of the experts' opinions efficiently.

There are many responsible factors for transmitting COVID-19 disease reported in various academic works and research studies. Our study is among the first to identify and aggregate those factors in a single study, and further, using those factors, we developed a Fuzzy decision-making framework with the help of hybrid MCDM techniques. In our knowledge, this is the first Fuzzy decision-making framework that analyzes the transmission vulnerability of COVID-19 among different cities. In this manner, our study will have important implications to the domain at the intersection of public healthcare risk-management and decision-making disciplines during a pandemic.

5.2 Policy implications

Countries across the world are reporting a surge of COVID-19 cases and a looming scarcity of essential health supplies such as masks, ventilators, and P.P.E. Therefore, the WHO calls for industries and policymakers to increase production by at least 40% [35] to fulfill the rising global demands. WHO also recommends preventive actions such as air travel restrictions, lockdown, quarantine, isolation, regulation of movement, travel history tracking, and closing borders.

For the effective implementation of preventive and mitigation measures, some improved communication and information-sharing approaches also need to be adopted that helps to build trust and increases awareness among the citizens. Some of them are social media awareness, COVID-19 dashboards, outdoor banners, print and electronic media, frequent preventive announcements in localities.

Healthcare centres in the U.S. reported the severe scarcity of testing kits[36] and P.P.E. kits[37] for the healthcare workforce and patients, revealing a rapidly growing imbalance between demand and supply for health facilities and medical resources. Now, there is a need for the best supply chain approaches, management, and strategic techniques to leverage limited resources, alleviate the imbalance between demand and supply, and increase the production of testing and P.P.E. kits. Therefore, our framework can assist local governments and health departments to provide preventive strategies and health facilities (number of beds[38], health workers, P.P.E., ventilators, and quarantine centres) based on the severity ranking in response to COVID-19.

5.3 Proposed Preventive Measures

Based on the rankings of clusters and their constituting factors, our study offers several effective preventive measures, and they also resonate with the directives issued by WHO. They are as follows:

(i) ***Social cohesiveness*** - It can be prevented by avoidance of social gatherings, religious places, and crowded places.

(ii) ***Hygiene unawareness*** - It can be eliminated by the implementation of water, sanitation, and hygiene (WASH) measures in communities, workplaces, homes, schools, marketplaces, and healthcare centres.

(iii) ***Close contact*** **-** People should maintain social distancing (at least 1 meter from adjacent persons), particularly those with respiratory symptoms, avoid social outings, and wear N95 masks at all times.

(iv) ***Disposal of medical waste of COVID patients*** **-** Proper segregation and disposal of healthcare waste produced by COVID-19 patients can eradicate this problem.

(v) ***Air quality*** – Improving the airflow and ventilation in living areas and workplace facilities can eradicate this problem.

6. Conclusion and future research directions

This study provides a fuzzy, hybrid multicriteria decision-making framework to identify vulnerable cities of COVID-19 transmission. We proposed a three-phase framework that consists of the FDM, FAHP, and FTOPSIS methodologies to achieve these research objectives. This framework enabled us to consider both objective and subjective factors simultaneously in the decision-making process. It can also assist policymakers and healthcare officials to formulate and improve preventive and mitigation measures for global pandemic problems such as the COVID-19 outbreak.

Initially, we identified thirty factors for the transmission of COVID-19 from the existing literature. These factors were drawn from six major clusters for the ease of analysis: *climatic* (C), *hygiene and safety* (H), *responsiveness to decision-making* (R), *social and demographic* (S), *economic* (E), and *psychological* (P). Then, we applied FDM to scrutinize those factors and found that twenty-five out of the thirty were relevant for further analysis. Therefore, we applied the FAHP method to determine the weights of each cluster and their constituting factors and found that *responsiveness to decision-making* (R) was the most critical among the six clusters. Within this cluster, *global travel* became the most significant factor for COVID-19 transmission. Within the *hygiene and safety* (H) cluster, *close contact* became the most important factor for COVID-19 transmission. Within the *social and demographic* (S) cluster, *social cohesiveness* became the most significant factor for COVID-19 transmission. Within the *psychological* (P) cluster, *panic-buying* became the most significant factor, while within the *climatic* (C) cluster, the *temperature* became the most significant factor. Finally, within the *economic* (E) cluster, *economic openness and democracy* became the major factor for COVID-19 transmission.

Next, we prepared a global ranking of the twenty-five factors, from which the top ten were: *global travel* (R2), *delay in travel restriction* (R4), *close contact* (H5), *social cohesiveness* (S2), *asymptomatic* (H1), *quarantine delay* (R1), *panic-buying* (P2), *shortage of P.P.E. kits* (H2), *population density* (S4), and *hiding travel history* (P4). This ranking can guide policymakers and healthcare officials to formulate quick and prompt mitigation strategies against the transmission of the COVID-19 pandemic.

Lastly, we applied the FTOPSIS method to rank ten different geographically located cities to decrease their vulnerability of COVID-19 transmission. From our ranking, we found that City 7 is the most vulnerable. In this way, our framework also helps to rank available geographical areas and identify the most susceptible city for policymakers, health administrators, and researchers worldwide. In summary, this study is the first attempt to identify the relevant factors for the transmission of COVID-19, compute the weights of those factors, rank them based on their severity, and finally, vulnerability-ranking of different cities based on those factors. Based on our findings and implications, healthcare strategies and policies can be revised to achieve a safe and healthy environment and considering all of these factors.

Despite these novel contributions, our study has few limitations and therefore offers some future research directions. First, COVID-19 is a new virus that can spread in different ways, and therefore virology and epidemiological research are in an evolving phase. In the future, our proposed framework can be modified by adding more factors that are responsible for COVID-19 transmission, and the entire analysis can be performed again. Second, our proposed framework is based on the expert's opinion, and these opinions could be biased. As a future extension of our study, our framework can be validated by a case-based analysis and thus verify the feasibility of a generalized framework.

Third, researcher and academician can extend this study by developing mathematical model for selecting vulnerable cities under all constraints.

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