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Challenges to COVID-19 vaccine supply chain: Implications for sustainable development goals

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ABSTRACT

The COVID-19 outbreak has demonstrated the diverse challenges that supply chains face to significant disruptions. Vaccine supply chains are no exception. Therefore, it is elemental that challenges to the COVID-19 vaccine supply chain (VSC) are identified and prioritized to pave the way out of this pandemic. This study combines the decision-making trial and evaluation laboratory (DEMATEL) method with intuitionistic fuzzy sets (IFS) to explore the key challenges of the COVID-19 VSC. The IFS theory tackles the uncertainty of key challenges while DEMATEL addresses the interlaced causal relationships among crucial challenges to the COVID-19 VSC. This work identifies 15 challenges and reveals that 'Limited number of vaccine manufacturing companies', 'Inappropriate coordination with local organizations', 'Lack of vaccine monitoring bodies', 'Difficulties in monitoring and controlling vaccine temperature', and 'Vaccination cost and lack of financial support for vaccine purchase' are the most critical challenges. The causal interactions along with mutual relationships among these challenges are also scrutinized, and implications for sustainable development goals (SDGs) are drawn. The results offer practical guidelines for stakeholders and government policy makers around the world to develop an improved VSC for the COVID-19 virus.

1. Introduction

The COVID-19 outbreak has posed a significant danger to the lives and well-being of billions of citizens around the world (Ivanov and Dolgui, 2021). The pandemic has implied huge changes in the way administration associations work (Narayanamurthy and Tortorella, 2021). In the current scenario, a shortfall of vaccines due to failure of the vaccine supply chain (VSC) will make circumstances more confounded (Chakraborty and Mali, 2020). A pandemic VSC is different than that of a traditional VSC because governments are directly procuring vaccines from the manufacturers bypassing the traditional chains of wholesalers and distributors (Abbasi et al., 2020). Hence, healthcare experts and VSC analysts are looking for proper policies and adequate strategies for appropriate vaccine manufacturing and distribution to fight against the COVID-19 pandemic. It is fundamental to look closely into pandemic VSCs and comprehend the challenges within to put an end to the devastating effects of the pandemic.

COVID-19 vaccines have been referred to as the light at the end of the tunnel' to finally return to some forms of normalcy (Warren and Lofstedt, 2021). Several manufacturing companies are racing to mass-produce COVID-19 vaccines (Kim et al., 2021). The COVID-19 VSC is particularly problematic due to the total volume required by each country to reduce infection rates and avoid lockdowns. To cover vaccination for 100% of the world's population with at least two doses per individual, the total quantity of vaccine dosages required is approximately 2–2.5 times than (16–20 billion doses) the current

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population (7 billion). Even for 75% inoculation, approximately 12–15 billion dosages of vaccines will be needed worldwide to handle the current outbreak (Rele, 2020). Hence, the key difficulties in the supply chain are to tackle such a huge volume through the complex networks of manufacturers, logistics providers, and medical facilities of different countries.

As a result, challenges of the COVID-19 VSC are different from VSCs of similar viruses for example, SARS outbreak in 2003, MERS outbreak in 2015, Ebola outbreak in 2018 and 2014, and Zika outbreak in 2016. Even though the current outbreak has been substantially covered in academic literature studying aspects such as the global supply chain (Ivanov, 2020), supply chain sustainability (Karmaker et al., 2020), and the sustainable and resilient supply chain (de Sousa Jabbour et al., 2020), little effort has been exerted to identify the challenges to the COVID-19 VSC. To address the aforementioned gap in the extant literature, this research investigates the challenges to the COVID-19 VSC using a novel Multi Criteria Decision Making (MDCM) method. Furthermore, inoculation is critical for achieving the UN Sustainable Development Goals (SDGs) because of its power to secure lives and create productive communities by strengthening health-care systems (Ratzan et al., 2019). Therefore, this study also draws implications of identified challenges on the SDGs.

The main contribution of this paper is to give a comprehensive understanding of the challenges of the COVID-19 VSC to facilitate the fight against the COVID-19 outbreak so that governments and all other concerned organizations are better prepared to develop contingency plans for monitoring and restructuring supply chains in pandemic situations. It is expected that the findings will also provide a lucid understanding of VSCs to address the issues in pandemic situations. Consequently, this study sheds light on the following research questions (RQs):

RQ 1: What are the critical challenges of the VSC due to the COVID-19 outbreak?

RQ 2: How can a systematic approach be developed to identify VSC challenges with limited previous research?

RQ 3: Which challenges have the most dominant influence in the COVID-19 VSC?

RQ 4: How to identify the inter-relationships among the challenges of the COVID-19 VSC to ensure smooth flow of VSC and provide practical insights for policymakers?

The objectives of this paper are as follows:

a) To investigate the major challenges in the COVID-19 VSC
b) To rank the challenges using the Intuitionistic Fuzzy DEMATEL (IF-DEMATEL) method
c) To identify the causal links among the challenges of VSC through the IF-DEMATEL framework
d) To provide practical insights for policymakers to overcome the challenges of VSC and understand their implications on SDGs

This study contributes to the extant research in multiple ways. First, it identifies challenges to the COVID-19 VSC. Second, it evaluates challenges using Intuitionistic Fuzzy Set (IFS) and DEMATEL to pinpoint the most critical ones. Third, it examines interrelationships among the challenges. Last, it draws implications of these challenges on SDGs to help policy makers for favorable policymaking.

The research paper is organized as follows. Section 2 presents the literature review. Section 3 describes the IF-DEMATEL methodology. Section 4 delineates and discusses the results. Section 5 explains the research implications. The final section portrays the conclusion and opportunities for future work.

2. Literature review

2.1. COVID-19 and vaccine supply chain

There has been an immense scientific breakthrough in the development of COVID-19 vaccines (Weintraub et al., 2021). Nations across the world have planned rollout of the approved vaccines to limit the transmission and damage due to the COVID-19 pandemic (Warren and Lofstedt, 2021). 17 vaccines entered Phase II trials and three vaccines (AstraZeneca, Moderna, and Pfizer) have been rolled out in the EU and the UK (Warren and Lofstedt, 2021). The World Health Organization (WHO) is collaborating with scientists, global health organizations, and non-profit business organizations for “Access to COVID-19 Tools (ACT)” to accelerate the COVID-19 response (Shervani et al., 2020). Availability of vaccine is critical to reduce the potential losses from the pandemic. Therefore, governments and academic institutions must respond and plan to make the vaccine available for the general population (Ocampo and Yamagishi, 2020). A critical concern is whether it will be possible for the pharmaceutical supply chains to scale up sustainably amidst the crisis (Yu et al., 2020).

Drawing on Simchi-Levi et al. (2008), a vaccine supply chain (VSC) is illustrated in Fig. 1. As depicted in Fig. 1, each vaccine will go through a development phase and a fulfillment phase when it is approved by the health authorities in different countries and regions. Availability of the vaccine will largely depend on removal of the bottlenecks in both the development and fulfilment phases of the supply chain (Rele, 2020). While developing new vaccines and assessing their effectiveness on humans are the key focus, it is also elemental to comprehend and address VSC issues to increase vaccine efficacy (Lee and Haidari, 2017).

According to WHO (2020), 42 COVID-19 vaccines are in clinical trials, whereas 151 potential vaccines are in preclinical assessment. These vaccine trials aim to enroll around 280,000 volunteers from 34 different countries (WHO, 2020). A speedy vaccine rollout is deemed to be a game changer and will allow the economy to recover faster due to lift of COVID-19 related restrictions (Goodwin, 2021).

Since the beginning of the pandemic, the topic of COVID-19 vaccine has been widely covered in the academic literature. For instance, Guttieres et al. (2021) modelled a framework to assess COVID-19 vaccination strategies. The authors purport that the proposed framework can help with scenario planning and assessing tradeoffs among vaccination strategies. Abbasi et al. (2020) concentrated on allocation of vaccine in the downstream supply chain and proposed a model for different distribution and allocation of vaccine. Jarrett et al. (2020) investigated the role of manufacturers to combat vaccine counterfeiting for implementing global traceability standards in the vaccine supply chain. Rele (2020) examines the vaccine development during a pandemic and identifies gaps and opportunities for combating future pandemics. While all these works related to COVID-19 vaccine are praiseworthy, they missed to specify challenges related to the COVID-19 VSC. Hence, this study investigates all possible challenges in the VSC of COVID-19 using a novel MCDM approach.

Additionally, inoculation play a critical role in achieving 14 of the 17 SDGs. It directly impacts poverty reduction, promotion of longer and healthier lives, women empowerment, and stability of health systems (León et al., 2019). The vaccine supply chain performance (VSCP) improvement can positively facilitate the fight against the COVID-19 pandemic and address SDGs by ensuring the vaccines are uniformly distributed across the globe.

2.2. Existing methods and rationale behind the proposed method

MCDM has been widely adopted for making decisions in complex situations (Garg, 2019; Wang et al., 2004). Among different MCDM approaches, the DEMATEL method is particularly advantageous for explicating the cause and effect relationships among multiple factors (Lin, 2013). The DEMATEL method is often combined with other approaches such as Interpretive Structural Modeling (ISM), Grey Theory System (GTS), Two-Sided Matching (TSM) for identifying the potential barriers to different systems (Ali et al., 2019; Kumar and Dixit, 2018; Li et al., 2020). For instance, Kumar and Dixit (2018) applied the ISM-DEMATEL approach to identify ten barriers to the e-waste

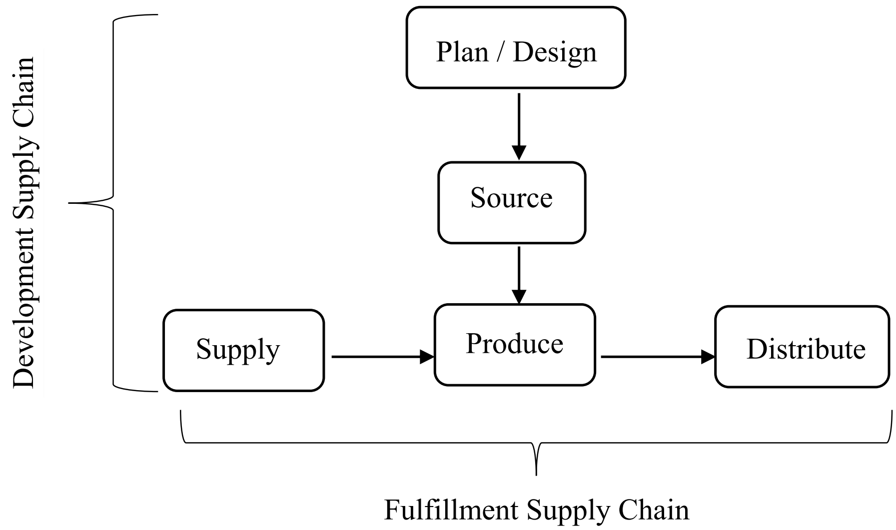

Fig. 1. A vaccine supply chain (VSC) (Simchi-Levi et al., 2008).

management practice implementation. Ali et al. (2019) used the Grey-DEMATEL method to assess food supply chain (FSC) risks. Li et al. (2020) developed the Multi-Attribute Two-Sided Matching approach for the probabilistic linguistic environment. However, the above combinations are not limitation free. ISM, TSM or GTS can only provide the hierarchy structure and do not consider much about the individual relationship. While GST can deal with the vagueness of expert opinions, its functionality is limited for managing cause-effect relations among different factors (Moktadir et al., 2018).

In this paper, IFS is combined with DEMATEL to identify the challenges to the COVID-19 VSC. The rationale for using IFS and DEMATEL for this research is manifold. First, IFS is recommended for capturing and managing the uncertainty and vagueness by taking into account both "degree of disagreement" and "degree of agreement" (Kahraman et al., 2020; Kumar and Garg, 2018). Second, the non-membership function, membership function, and degree of hesitancy in the IFS theory allow to represent 'support', 'opposition', and 'neutrality' in any complex situation (Kahraman et al., 2020; Kumar and Garg, 2018; Wang and Chen, 2017). Third, the hesitancy degree enables the IFS to better model the vague data that can emerge when the policy-makers are uncertain about their inclinations. Last, IFS can resolve the weakness of DEMATEL which is good at capturing cause and effect relationships but performs poorly in capturing vagueness (Bai and Sarkis, 2013). Therefore, the combination of IFS and DEMATEL, referred to as IF-DEMATEL, models the vague and questionable issues in human judgments. It also overcomes weaknesses of the DEMATEL technique and improves the accuracy of the challenge identifying procedure and interrelationships among the challenges.

3. Methodology

This work combines three stages. In the first stage, interviews are conducted with 12 experts from the healthcare industry and VSC to filter as well as add to the list of challenges found through the literature survey. In the second stage, a questionnaire consisting of collected challenges was given to the experts who responded on a linguistic scale. In the third and final stage, data are analyzed using IF-DEMATEL. The flow of work for this study is illustrated in Fig. 2.

3.1. Data collection approach

In this study, a multi-stage online survey is conducted to collect data. The initial phase of the survey is performed through a questionnaire (see Appendix B) distributed to experts via email and social media platforms. Next, a list (Table 1) of experts of 12 members is identified based on their knowledge of VSC and healthcare systems. As depicted in Table 1, experts are from all domains of VSC, such as vaccine manufacturer, vaccine buyer, and vaccine distributor. Furthermore, experts from knowledge-based institutions and government advisers are also included to better comprehend VSC challenges. After emailing and circulating the questionnaires, follow-up calls are made to the specialists to ensure they participated in the survey. The initial phase of the survey takes 52 days in total to compile the responses from the experts.

Twelve challenges are identified from the literature review, as shown in Table B1 (Appendix B). Following the guidelines of Tsai et al. (2021), a challenge included or excluded only if at least 9 of the 12 experts (i.e., 75%) agreed or disagreed about its connections to VSC. In this process, five challenges are added to the list of 12 challenges, and two challenges, i.e., 'Immunization program delivery strategies' and 'Topographical boundaries', are removed from the list. Finally, 15 COVID-19 VSC challenges are selected. Table 2 list these challenges and indicates whether they are collected from literature or experts' opinions. These 15 selected COVID-19 VSC challenges were sent to the experts once again for confirmation and validation. After finding the final prominence-relation map, results were again verified through emails to the experts.

Listed challenges are grouped into five meaningful categories: manufacturing challenges, behavioral challenges, last-mile delivery challenges, cold chain challenges, and organizational challenges. Table 2 shows these categories.

3.2. Intuitionistic fuzzy set (IFS) theory

The Fuzzy Set Theory (FST) is formulated to deal with uncertainty and vagueness while analyzing information (Zadeh, 1996). IFS is an addition to the FST. It is described through a non-membership along with membership function, and a hesitancy degree that represents opposition, support, and neutrality in expressing any information (Gan and Luo, 2017; Ocampo and Yamagishi, 2020). The difference between FST and IFS is that IFS has the ability to handle the expert's vagueness (Govindan et al., 2015). Moreover, IFS theory has the capability to model unknown and uncertain data (Ocampo and Yamagishi, 2020). When experts and decision-makers are not absolutely sure about their opinions, the IFS theory works better than FST. Some basic concepts of IFS are illustrated in the following:

Definition 1. Consider X is a non-empty, finite set, and F is a standard fuzzy set if ∃ a membership function μ_F (x), when μ_F (x): X → [0,1].

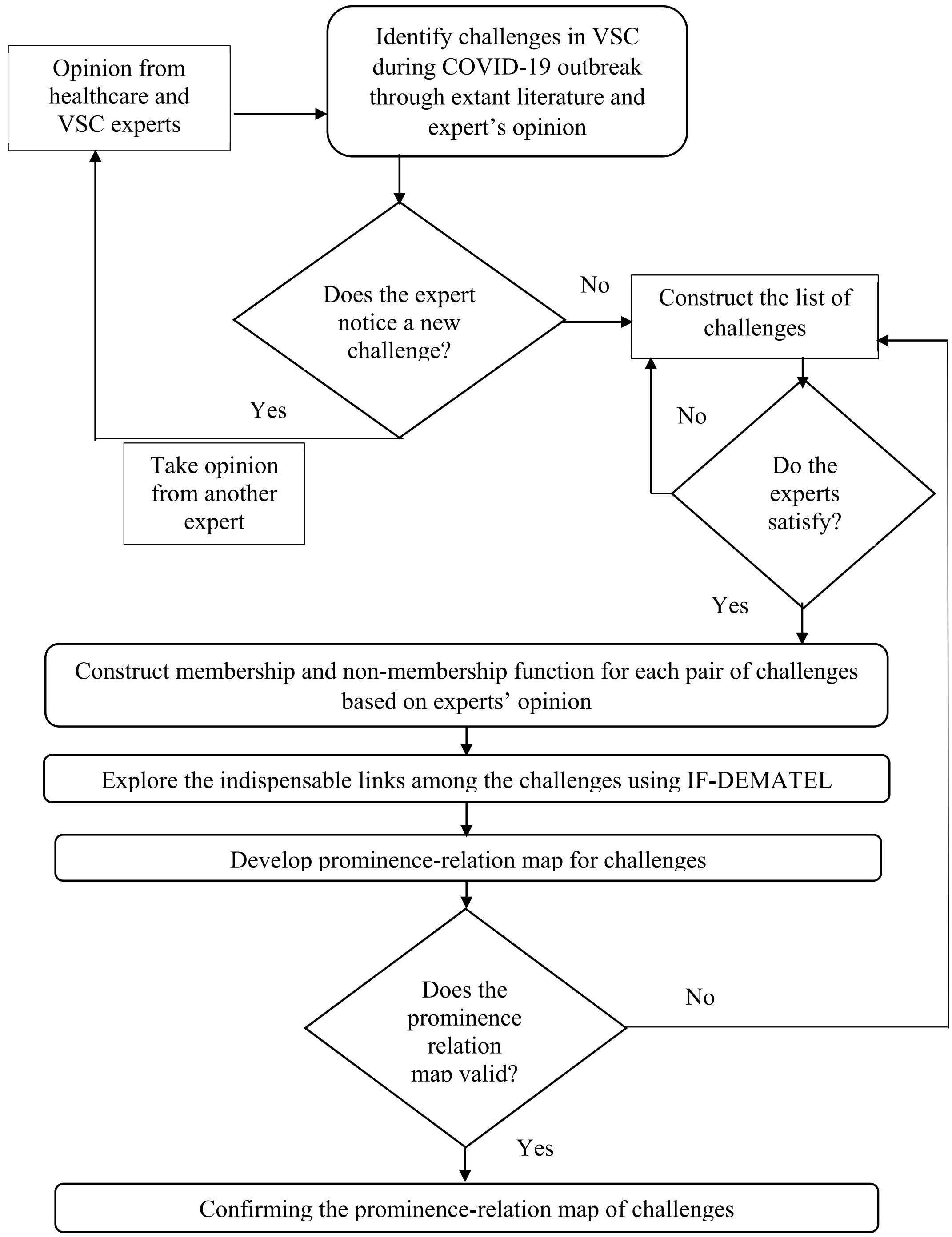

Fig. 2. The flow of work in this study.

Suppose A ⊆ X and A = {x, μ_F (x): x ∈ X, μ_F (x) ∈ *[0,1]*}, when membership function μ_F *(x)* is a function of x in standard set F (Ocampo, 2019; Ocampo and Yamagishi, 2020).

Definition 2. IFS in X can be expressed as

$$F = \{x,\ \mu F\ (x),\ vF(x):\ x\hat{I}\ X\},\ \text{when } X \text{ is a fixed set} \tag{1}$$

In eqn. (1), μ_F *(x): X → [0,1]* as well as ν_F *(x): X → [0,1]* are expressed, considering $0 \leq \mu_F\ (x) + \nu_F\ (x) \leq 1$. μ_F *(x)* signifies the membership degree of lack of knowledge, and ν_F (x) denotes non-membership degree of element $x \in X$ to that fixed F (Atanassov, 1999).

$$\pi F(x) = 1 - \mu F(x) - vF(x),\ \text{where } 0 \leq \mu F(x) \leq 1 \tag{2}$$

Definition 3. A triangular fuzzy number is expressed as a triplet F = (l, m, u), μ_F *(x)* and ν_F *(x)* is expressed as follows where l, m, and u are the lowest possible value, the most promising value, and the highest possible value respectively to explain a fuzzy event (Balli and Korukoğlu, 2009; Ocampo, 2019).

Table 1
List of interview participants.

Experts	Designation	Experience	Firms	Role in VSC
E1	Principal Scientific Officer, Microbiology Department	12 years	Autonomous-Government Organization (Microbiology Department)	Government Adviser
E2	Chairman	48 years	Public Medical	
E3	Principal Scientific Officer, Medicine Department	11 years	Autonomous-Government Organization (Medicine Department)	
E4	Medical Officer	07 years	Government Hospital	Knowledge Based Institution
E5	Professor, Virology Department	18 years	Public University	
E6	Managing Director	07 years	Raw Materials Supplier	Vaccine Manufacturer
E7	Secretary General	21 years	Drug Administration	
E8	Production Planning Executive	06 years	Healthcare Industry	
E9	Supply Chain Executive	04 years	Healthcare Industry	Vaccine Buyer
E10	Chairman	10 years	Pharmaceutical Industry	
E11	Managing Director	06 years	Pharmaceutical Industry	Vaccine Distributor
E12	Senior Merchandiser	08 years	Pharmaceutical Industry	

$$\mu F(X) = \begin{cases} 0 & x < l \\ \dfrac{(x-l)}{(m-l)} & l \le x \le m \\ \dfrac{(u-x)}{(u-m)} & m \le x \le u \\ 0 & x > u \end{cases} \tag{3}$$

$$vF(X) = \begin{cases} 1 & x < l \\ \dfrac{(l-x)}{(l-m)} & l \le x \le m \\ \dfrac{(x-u)}{(m-u)} & m \le x \le u \\ 1 & x > u \end{cases} \tag{4}$$

Definition 4. The IFS is a mapping E → [0,1] × *[0,1]*, and this is represented as μ_F (x), v_F *(x)* when x ∈ E. E is fixed universe, whereas μ_F *(x)* and v_F *(x)* are of x to F ∀ μ_F (x) + v_F (x) ≤ 1. Map of [0,1] × [0,1] → R can be expressed as "crispification operation" where, for IFS theory E = R. Suppose the "crispification operation" can be explained as D_λ: [0,1] × [0,1] → R and F be an IFS. A standard fuzzy set can be transformed from IFS (F) and evaluated that set with the help of a defuzzification method (Angelov, 1995; Anzilli and Facchinetti, 2016).

Definition 5. Suppose F be an IFS. From Definition 4, the Transformation of F into a standard fuzzy set is explained as:

$$D\lambda(F) = \{x, \mu F(x) + \lambda \pi F(x),\ vF(x) + (1-\lambda)\pi F(x) \forall\ x\ in\ X\} \tag{5}$$

where, D_λ *(F)* has a μ_λ *(x)*, which is the summation of μ_F *(x)* and $\lambda\mu_F$ *(x)* and λ can be any value between 0 and 1 (Anzilli and Facchinetti, 2016; Ocampo and Yamagishi, 2020). Suppose for λ = ½, the minimization problem can be expressed as $\min_{\lambda\in[0,1]} d(D_\lambda(F), F\Big)$. Where, d will be the

Table 2
List of challenges of vaccine supply chain.

Main Category	Code	Challenges	Descriptions	References
Manufacturing challenges	C1	Vaccination cost and lack of financial support for vaccine purchase	The development of a financially affordable vaccine is vital for the successful alleviation of the dangerous COVID-19 pandemic. Vaccination cost and lack of financial support for vaccine purchase for manufacturing and maintaining a cold chain restrict the vaccine development and distribution.	Expert Opinion
	C2	Limited number of vaccine manufacturing companies	To inoculate the global population, a large volume of vaccines is needed. Limited number of companies who can successfully produce effective vaccines is a key challenge, which can restrict vaccination programs around the world.	Pagliusi et al. (2020)
	C3	Lack of accurate vaccine demand forecast	Vaccine demand of a region can be affected by per capita income, vaccine-related convictions, knowledge of medical care staffs, urbanization, and vaccination missions. The inability to predict the variables mentioned above can reduce the efficacy of COVID-19 VSC.	Dizbay and Öztürkoğlu (2021)
Behavioral challenges	C4	Consumers' unwillingness to vaccinate	Consumers can reject vaccines because of fear of potential side effects from vaccines, social dogma, misinformation, and vaccination-related negative	Khubchandani et al. (2021)

(continued on next page)

Table 2 (*continued*)

Main Category	Code	Challenges	Descriptions	References
			beliefs or skepticism.	
	C5	Inadequate positive vaccine marketing	COVID-19 vaccine acceptance largely depends on the positive vaccine marketing. Inadequate positive vaccine marketing can negatively influence public perception of COVID-19 vaccines.	Expert Opinion
Last mile delivery challenges	C6	Unavailability of volunteers for vaccine trials	As phase II and III need human trials, the lack of volunteers' availability can significantly slow down the development of COVID-19 vaccines.	Richards (2020)
	C7	Long distance between vaccine stores and vaccination camps	A long distance between vaccine stores and vaccination camps can negatively impact vaccine distribution programs.	Antal et al. (2021)
	C8	Lack of proper planning and scheduling	Lack of proper planning and scheduling can influence immunization enrollment, vaccine purchase, storage, and distributions.	Antal et al. (2021)
	C9	Increase in acquisition lead time	Delay in acquisition decisions may increase the acquisition lead time and negatively hamper timely distribution of the vaccine.	Expert Opinion
Cold chain challenges	C10	Lack of proper storage systems	Lack of proper storage system in remote locations can delay the delivery of vaccines, which, in turn, may reduce the effectiveness of the COVID-19 VSC.	Rosen et al. (2021)
	C11	Difficulties in monitoring and controlling vaccine temperature	Some COVID-19 vaccines are temperature sensitive. Inability to maintain the recommended temperature while transferring vaccines from manufacturers to consumers may reduce the efficacy of VSC, especially in the tropical regions.	Lin et al. (2020)
Organizational challenges	C12	Difficulty of tracking vaccinated population	Difficulty of tracking of vaccinated population can reduce the transparency and equal distribution of the COVID-19 vaccine. Countries without a central health registry of their population will face challenges to monitor and track the total number of vaccinated populations.	Hodgson et al. (2021)
	C13	Inappropriate coordination with local organizations	Inappropriate coordination with local healthcare organizations may impede the rapid vaccine supply and distributions by creating communication gaps. Coordination with local organizations is customary for proper distribution of the COVID-19 vaccine and the quick response.	Expert Opinion
	C14	Lack of vaccine monitoring bodies	Lack of vaccine monitoring bodies can hamper purchase, delivery, monitoring, and transparency in the VSC.	Expert Opinion
	C15	Lack of correspondence between the VSC members	Supply chains around the globe are confronting significant interruption, and the lack of correspondence between supply chain members can impede a proper production and distribution of the COVID-19 vaccine.	Zhu et al. (2020)

Euclidean intervals and the set can be expressed as:

$$\mu\lambda(x) = 0.5(1 - vF(x) + \mu F(x)) \quad (6)$$

3.3. DEMATEL method

DEMATEL is a graph-theoretical approach for illustrating causal relationships between a set of complex factors or challenges (Govindan et al., 2015). In this method, elements of a system are represented by vertices, and causal relationships among elements are represented by edges (Ocampo and Yamagishi, 2020). This method can specify the "correlativity" among the listed challenges and predict the significance of each challenge (Gan and Luo, 2017). The fundamental processes of DEMATEL are as follows (Biswas and Gupta, 2019):

Step 1: Construction of a Direct-Relation Matrix (DRM), which includes a pairwise comparison of causal relationships between C number elements. The pairwise comparison can be developed from the performance of an expert group containing N members. The direct-relation matrix $X^m = (x_{ij}^m)_{c\times c}$ for the mth expert where x_{ij} shows the influence of the challenge C_i on challenge C_j. The scale shown in Table 3 can be followed.

The aggregate direct-relation matrix, $X, \forall X^m$ where $m = 1, 2, \ldots\ldots, N.$ and $w_m \in R$ is considered the significance of the mth expert. X can be expressed as follow:

$$X = (cij)_{c\times c}\left(\frac{\sum_{m=1}^{N} W_m x_{ij}^k}{\sum_{m=1}^{N} W_m}\right) c \times c \quad (7)$$

Step 2: Normalization of aggregate DRM, which may be developed following Equations (8) and (9).

$$G = h^{-1}X \quad (8)$$

$$h = max\left(\max_{1\le i\le c}\sum_{j=1}^{c} xij,\ \max_{1\le j\le c}\sum_{i=1}^{c} xij\right) \quad (9)$$

Step 3: Calculation the Total Relation Matrix (TRM) T, which may be illustrated as ($T = [t_{ij}]_{C\times C}$) through Equation (10) (Ding et al., 2019). T represents the influential relationship among all listed challenges.

$$T = G + G^2 + G^3 + G^4 + G^5 + \ldots.. = \sum_{i=1}^{\infty} G^i = G(I\_G)^{-1} \quad (10)$$

where t_{ij} represents the element of T in jth column and ith row, and I represent a $C \times C$ identity matrix.

Step 4: Categorization of the challenges into the net effect and the net cause. D_i and R_j identify the summation of rows and the summation of columns, respectively. A graph of cause and effect is gathered by mapping the numerical value of ($D_i + R_j$, $D_i - R_j$).

$$D_i\left(\sum_{j=1}^{n} t_{ij}\right)_{C\times 1} = (t_i)_{C\times 1} \quad (11)$$

$$R_j = \left(\sum_{i=1}^{n} t_{ij}\right)_{1\times C} = (t_j)_{1\times C} \quad (12)$$

The "Prominence Vector" ($D_i + R_j$) expresses the comparative significance of each challenge. Those challenges in the "Relation Vector" ($D_i - R_j$) belong to the net cause group when $t_i - t_j > 0$, $i = j$. The challenges will be in the net effect group when $t_i - t_j < 0$, $i = j$.

Table 3
Evaluating scale for causal influence.

Numerical Value	Remarks
0	No impact (N)
1	Low impact (L)
2	Moderate impact (M)
3	High impact (H)
4	Extremely high impact (EH)

Step 5: Construction of the "Prominence-Relation Map". Fig. 3 represents the ($D_i + R_j$, $D_i - R_j$) mapping of the challenges.

3.4. The intuitionistic fuzzy DEMATEL (IF-DEMATEL) method

The IF-DEMATEL method used in this study includes the following steps:

Step 1: Define the vaccine supply chain challenges.

The VSC challenges of COVID-19 vaccines are identified through semi-structured interviews followed by an iterative and deductive process. The list of these challenges is presented in Table 2 along with the corresponding codes.

Step 2: Construct the DRM.

The matrix which was developed by a group of 12 experts, including seven experts from VSC and five experts from the healthcare industry. The experts' group expressed x_{ij} values in IFS. Expert collaboration and consultations were conducted to secure that these challenges in the initial direct-relation matrix are not whimsical. The experts were requested to deliver the value of $\mu_F(x)$ and $v_F(x)$ on the causal influence of c_i on c_j. The values of $\pi_F(x)$ are identified from Equation (2). Table A1 illustrates the initial-DRM in IFS where all the elements are specified as a 2-tuple. The fundamental concept of 2-tuple is presented in Definition 4.

Step 3: Construct the corresponding membership function.

In this step, the corresponding membership function of the equivalent fuzzy subset is constructed. Construction of the membership function required defuzzification of the IFS value (Ocampo and Yamagishi, 2020). Following Anzilli and Facchinetti (2016), a two-stage defuzzification process is adopted. In the first stage, IFS is converted into a standard fuzzy subset using Equation (6). Table A2 illustrates the Initial-DRM in the standard fuzzy subset. For example,

$$\mu(x_{24}) = \mu(0.3,\ 0.1) = 0.5(1 - vF(x) + \mu F(x)) = 0.5(1 - 0.1 + 0.3) = 0.6$$

Step 4: Conduct the defuzzification process from the standard fuzzy subset.

In the second stage, a defuzzification function f is adopted, which would map f: $\mu(x) \rightarrow R$ (Anzilli and Facchinetti, 2016; Ocampo and Yamagishi, 2020). The membership function(s) in Table A2 is assigned to a triangular fuzzy number $(l, m, u) = (0,4,4)$ (Ocampo and Yamagishi, 2020). Equation (3) can be rewritten as:

$$\bar{x} = (m - l)\mu(\bar{x}) + 1 \quad (13)$$

where $\bar{x}$ and $\mu(\bar{x})$ show the "crisp" value and the membership function, respectively. For example,

$$\bar{x}_{24} = l + \mu\left(\bar{x}_{24}\right)(m - l) = 0 + 0.6 \times (4 - 0) = 2.4$$

The crisp value in the form of Initial-DRM is illustrated in Table A3.

Step 5: Construct the Normalized DRM.

The Normalized DRM is found using Equations (8) and (9), when $h = 37.8$. The matrix is illustrated in Table A4.

Step 6: Develop the TRM.

The TRM is generated following Equation (10) and is illustrated in Table A5 (Ocampo and Yamagishi, 2020). The (D_i - R_j) and ($D_i + R_j$) vectors are shown in Table 4 and Table 5 and are computed using Equations (11) and (12) (Kumar et al., 2020). The net cause and the net effect are categorized in Tables 4 and 5.

Step 7: Develop the Prominence (P) - Relation (R) Map.

Fig. 5 represents the Prominence (P) – Relation (R) Map, developed based on ($D_i + R_j$, $D_i - R_j$) coordinates.

Fig. 4 expresses all the steps of the IF-DEMATEL method.

4. Results and analysis

In this section, cause and effect group challenges are identified. Next,

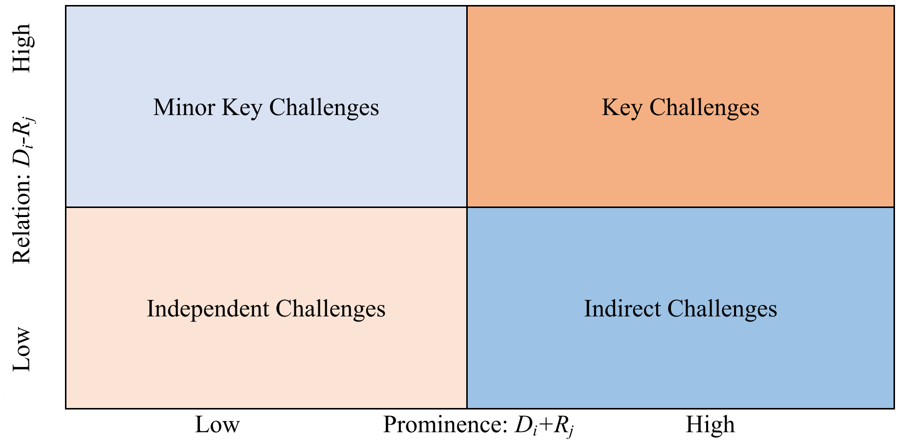

Fig. 3. The "prominence-relation map".

Table 4
Relation vector (D_i - R_j).

Rank	Cause Group	D_i - R_j	Rank	Effect Group	D_i - R_j
1	C14	0.5674	1	C4	−0.1246
2	C11	0.5208	2	C15	−0.1649
3	C12	0.3663	3	C3	−0.1678
4	C7	0.1927	4	C10	−0.1910
5	C2	0.1793	5	C8	−0.2120
6	C5	0.1507	6	C6	−0.2310
7	C13	0.1179	7	C9	−0.3874
			8	C1	−0.6167

Table 5
Prominence vector (D_i+ R_j).

Rank	Challenges	D_i	R_j	(D_i+ R_j)
1	C2	5.6363	5.4570	11.0933
2	C13	5.2156	5.0977	10.3133
3	C14	5.3728	4.8054	10.1782
4	C11	5.3447	4.8236	10.1683
5	C1	4.7131	5.3298	10.0429
6	C12	4.8995	4.5332	9.4327
7	C15	4.6148	4.7797	9.3945
8	C3	4.5891	4.7569	9.3460
9	C9	4.3427	4.7301	9.0728
10	C8	4.1831	4.3951	8.5782
11	C5	4.3526	4.2019	8.5545
12	C4	4.1237	4.2483	8.3720
13	C10	4.0444	4.2354	8.2798
14	C7	3.9087	3.7160	7.6247
15	C6	3.6775	3.9085	7.5860

challenges are ranked based on the prominence vector. Finally, a prominence-relationship map of the challenges to the COVID-19 VSC is created to reveal the interactions among the challenges. The causal and effect group expresses the interdependence relationships and the influential value between challenges that provide relatable visualizations and appropriate structural relationships (Lin, 2013).

4.1. Cause group

According to the experimental data set (D_i – R_j), seven challenges are in the cause group (see Table 4). These challenges are: "Limited number of vaccine manufacturing companies (C2)", "Inadequate positive vaccine marketing (C5)", "Long distance between vaccine stores and vaccination camps (C7)", "Difficulties in monitoring and controlling vaccine temperature (C11)", "Difficulty of tracking vaccinated population (C12)", "Inappropriate coordination with local organizations (C13)", and "Lack of vaccine monitoring bodies (C14)". This group of net causes has a substantial impact (D_i) than the group of net effect (R_j). This group of challenges needs to be addressed immediately and should be removed quickly (Karuppiah et al., 2020). Consequently, each of these seven challenges is vital to all relevant VSC stakeholders for deducing a proper approach to manage the uncertainty in the COVID-19 VSC.

4.2. Effect group

Eight challenges are in the effect group (see Table 4). These are: "Vaccination cost and lack of financial support for vaccine purchase (C1)", "Lack of accurate vaccine demand forecast (C3)", "Consumers' unwillingness to vaccinate (C4)", "Unavailability of volunteers for vaccine trials (C8)", "Increase in acquisition lead time (C9)", "Lack of proper storage systems (C10)", and "Lack of correspondence between the VSC members (C15)".

The net effect group is relatively easy to influence because their (D_i - R_j) value is negative (Ocampo and Yamagishi, 2020). Therefore, these challenges should be given priority after the cause group challenges are managed. The ranking of the factors according to the (D_i - R_j) scores are C14 > C11 > C12 > C7 > C2 > C5 > C13 > C4 > C15 > C3 > C10 > C8 > C6 > C9 > C1.

4.3. Prominence vector

The (D_i+ R_j) showed in Table 5 portrays the relative importance of the challenges. The larger is the value of (D_i+ R_j) for a specific challenge, the greater is the vitality or significance or importance of the challenge (Bai and Sarkis, 2013). As depicted in Table 5, 'Limited number of vaccine manufacturing companies (C2)' holds the highest (D_i+ R_j) value. It means it is the most significant challenge of the COVID-19 VSC. According to the (D_i+ R_j) values, the ranking of the challenges are as follows: C2 > C13 > C14 > C11 > C1 > C12 > C15 > C3 > C9 > C8 > C5 > C4 > C10 > C7 > C6.

4.4. Correlations between the challenges

Critical challenges are recognized by mapping the challenges in the prominence relationship map (see Fig. 5). In this map, all the challenges are categorized into four categories: minor key challenges (high relation, low prominence), key challenges (high relation, high prominence), independent challenges (low relation, low prominence), and indirect challenges (low relation, low prominence) (Ocampo and Yamagishi, 2020). Challenges situated over the x-axis are the cause group challenges, and challenges that are under the x-axis are effect group challenges. All these challenges are in the effect group, which means they are affected by the cause group challenges.

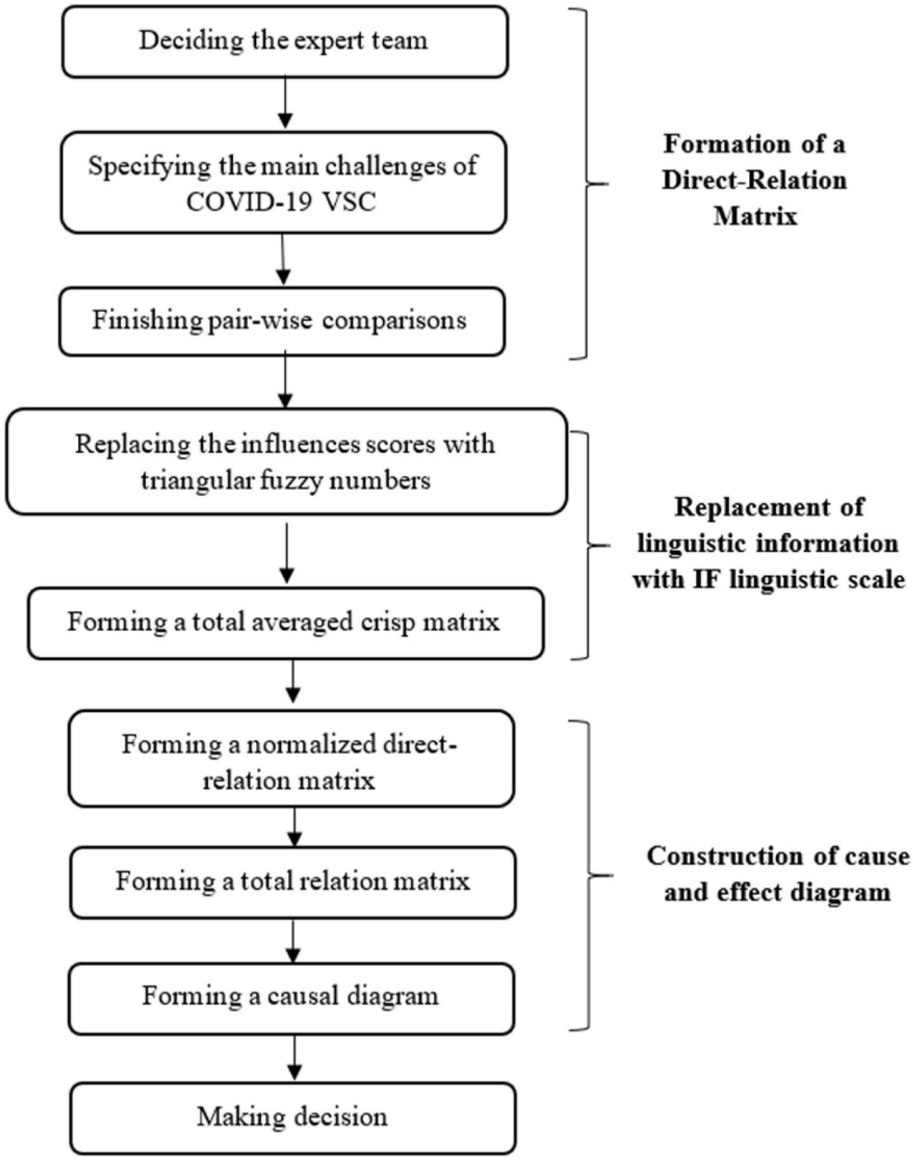

Fig. 4. Steps of IF-DEMATEL approach (Govindan et al., 2015).

As depicted in Fig. 5, the minor key challenge category consists of only one challenge, which is "Long distance between vaccine stores and vaccination camps (C7)". This challenge has minimal impact on other challenges, and its potential significance is low. The independent challenges category also contains one challenge, which is "Unavailability of volunteers for vaccine trials (C6)". It means that this challenge is not affected by other challenges.

The indirect challenges category consists of seven challenges. These are: (1) "Vaccination cost and lack of financial support for vaccine purchase (C1)", (2) "Lack of correspondence between the VSC members (C15)", (3) "Lack of accurate vaccine demand forecast (C3)", (4) "Increase in acquisition lead time (C9)", (5) "Lack of proper planning and scheduling (C8)", (6) "Consumers' unwillingness to vaccinate (C4)", and (7) "Lack of proper storage systems (C10)". Indirect challenges have high significance but low relation.

The key challenges category comprises six challenges. These are ranked as follows: (1) "Limited number of vaccine manufacturing companies (C2)", (2) "Inappropriate coordination with local organizations (C13)", (3) "Lack of vaccine monitoring bodies (C14)", (4) "Difficulties in monitoring and controlling vaccine temperature (C11)", (5) "Difficulty of tracking vaccinated population (C12)", and (6) "Inadequate positive vaccine marketing (C5)". Key challenges have the most influence on other challenges. All these challenges are in the cause group and must be given the highest priority for successful administration of the COVID-19 VSC. Focusing on and overcoming these challenges will assist governments worldwide to formulate a proactive and responsive plan for efficient and effective vaccine supply and distribution.

5. Discussions and implications

This section compares and contrasts five most significant challenges based on their prominence values against existing literature as well as presents contributions to theory.

5.1. Research implications of major challenges

Table 5 reveals that "Limited number of vaccine manufacturing companies (C2)" primarily affects other challenges such as "Vaccination cost and lack of financial support for vaccine purchase (C1)", "Increase in acquisition lead time (C9)", and "Lack of proper storage systems (C10)". This finding is in line with Carmichael (2021), who reports the

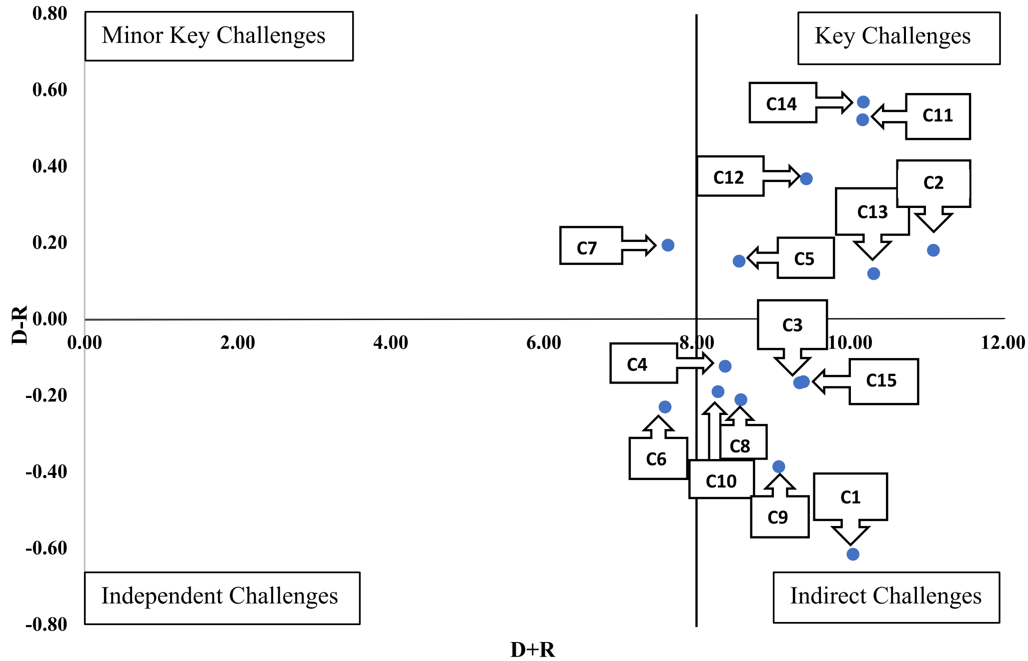

Fig. 5. The prominence-relation map of the challenges to the COVID-19 vaccine supply chain.

presence of only six vaccine manufacturing companies namely, "AstraZeneca", "Novavax", "Johnson & Johnson", "Moderna", "Pfizer and BioNTech", and "Sanofi and GlaxoSmithKline" with a total capacity of approximately 10 billion doses. This challenge is also important to address because Kim et al. (2021) state that about 10–11 billion vaccine doses are required to interrupt virus transmission successfully. According to Bozorgmehr et al. (2021), Pfizer-BioNTech, Moderna, and AstraZeneca are already encountering manufacturing delays. The findings of this research explain these delays in manufacturing because it has been observed that there is an effect of "Limited number of vaccine manufacturing companies (C2)" on the "Increase in acquisition lead time (C9)".

"Inappropriate coordination with local organizations (C13)" is the next significant challenge for the COVID-19 VSC. Results show that "Inappropriate coordination with local organizations (C13)" substantially affects "Lack of accurate vaccine demand forecast (C3)", "Unavailability of volunteers for vaccine trials (C6)", "Lack of proper planning and scheduling (C8)", and "Lack of correspondence between the VSC members (C15)". Pandemic vaccines are often procured by governments and then distributed to local healthcare facilities for mass vaccination of a country's population. It has been found out from the expert interviews that the collaboration between the local level and state level is essential to a successful vaccination campaign. For instance, Henao-Restrepo et al. (2015) argue that appropriate coordination of local and state organizations for the Ebola pandemic resulted in a faster vaccination process. However, the correspondence between the local and state-level governments has been inconsistent on many occasions. For instance, according to Freed (2021), it is poorly understood whether and how individuals will be informed about the second dose of the vaccine. Furthermore, Lee and Haidari (2017) suggest that without proper coordination between the state level and the local level, vaccine shortages and predictability of vaccine demand can become very problematic and hamper the effective and timely distribution of vaccines. Hence, future research can explore different ways to establish appropriate coordination between local and state-level organizations to ensure VSC's effectiveness and efficiency (Shamsi and Torabi, 2018).

"Lack of vaccine monitoring bodies (C14)" is in the third rank in the listed challenges. This challenge predominantly affects other challenges such as "Lack of accurate vaccine demand forecast (C3)", "Unavailability of volunteers for vaccine trials (C6)", "Lack of proper planning and scheduling (C8)", "Increase in acquisition lead time (C9)", and "Lack of correspondence between the VSC members (C15)". Furthermore, it indirectly affects "Consumers' unwillingness to vaccinate (C4)" and "Lack of proper storage systems (C10)". Though the literature on VSC does not clearly state the need for a centralized vaccine monitory body, Moon et al. (2015) contend that weak coordination between global operational response to Ebola pandemic was one of the most critical constraints. In a similar tone, Liu et al. (2020) argue that a successful COVID-19 vaccination implementation will need a strong collaborative network of government agencies, research institutions, and non-profit organizations. Furthermore, according to Jarrett et al. (2020), all these networks of organizations need to be monitored centrally to ensure the efficacy, safety, and quality of each vaccine. Consequently, a potential area for future research can be different governance mechanisms that these monitoring bodies can implement to ensure the proper distribution of vaccines (Marhold and Fell, 2021).

"Difficulties in monitoring and controlling vaccine temperature (C11)" holds the fourth rank in the listed challenge. It substantially affects "Lack of proper storage systems (C10)" and indirectly affects "Vaccination cost and lack of financial support for vaccine purchase (C1)". This finding is in line with the white paper by AMETEK, (2020), which reports that all approved COVID-19 vaccines need to maintain a cold chain during manufacturing, transportation, and distribution to the healthcare facilities. In a similar vein, Chen et al. (2015) purport that proper storage facilities (e.g., refrigerators, freezers, cold rooms) and vehicles with temperature monitoring systems need to be developed for successful vaccination programs. Burgos et al. (2021) also highlight the criticality of tracking vaccine temperature in the entire VSC. Thus, future research needs to address transportation and cold chain-related problems in the VSC (Dai et al., 2021).

Finally, the fifth-ranked challenge is "Vaccination cost and lack of financial support for vaccine purchase (C1)". The extant VSC literature also supports the significance of this challenge. For instance, Bollyky and Bown (2020) contend that vaccine nationalism makes it difficult for low-income countries to get adequate vaccine supply. Additionally, according to Weintraub et al. (2021) reports withdrawal of the United

States and Russia from COVAX which will further complicate the vaccine supply to the low and middle-income countries. Furthermore, Kohli et al. (2021) argue that the speed at which an effective vaccine is accessible to all countries will determine to what extent governments can prevent mortality and morbidity. The challenge of lack of financial support for vaccines previously found to be critical for the rotavirus vaccine. According to Kim et al. (2021), even though Food and Drug Administration (FDA) endorsed the rotavirus vaccine in 2006 yet, last year, only 60% of the world's kids were given the rotavirus vaccine. Therefore, it is customary to look into financial support mechanisms, and a potential area to explore by future research is supply chain finance (Chen et al., 2020).

As illustrated in the above paragraphs, the challenges identified in this research are critical. Therefore, they need the greatest attention from researchers across the globe so that it is possible to pinpoint and suggest efficient solutions to overcome these challenges at the soonest possible time. Consequently, this paper contributes to the extant literature in the following ways.

- It adds to the ongoing efforts by scholars and corroborates research on COVID-19 VSC.
- It identifies critical challenges to COVID-19 VSC from literature and substantiates and validates these challenges with expert opinions from all stages of VSC.
- It also highlights the interrelationships between COVID-19 VSC challenges.
- It proposes a novel MCDM approach, the IF-DEMATEL technique, to rank and prioritizes the identified challenges.
- It demonstrates how to remove vagueness and improve the accuracy in identifying challenges which future researchers can replicate to apply in situations where it is challenging to avoid ambiguity of expert opinions.
- It signifies the importance of systematically studying COVID-19 VSC for extracting key insights and pinpoints attention to vaccine supply chain including manufacturing, distribution, organization, and coordination for successfully vaccinate global population.

5.2. Managerial and SDG implications

This study has important implications for managers and policy makers worldwide. With a thorough understanding of COVID-19 VSC challenges, managers, policy makers, and governments will be able to define which challenges can be given less attention and which require more attention. The mapping of the challenges in the prominence-relation map will assist the key decision makers in the COVID-19 VSC to appropriately allocate necessary resources and financial investments. Further, the IF-DEMATEL method identifies the causal relationships between the challenges of COVID-19 VSC, and thereby it provides the managers with a comprehensive decision-making framework. Decision makers in the COVID-19 VSC can categorize and rank these challenges as per their relation vector and prominence vector and explore the dominance of one challenge over other challenges depending on the net negative and positive impacts. The IFS theory permits the decision-makers to locate the 'uncertainty' and 'vagueness' of human decisions, thus, removing the associated ambiguity in the decision-making process. Policy-makers can effectively take their strategic decisions by identifying the relative influences of VSC challenges on each other. Policy-makers can also improve the vaccine distribution and delivery processes by identifying the interactions and causal links among the challenges.

While every challenge is relevant and must be handled for successful execution of COVID-19 VSC, different categories will help managers to deal with the most significant ones first. For instance, it is elementary to concentrate on the cause group challenges at first because of their impact on the effect group. Therefore, managers dealing with COVID-19 VSC must strive to overcome the cause group challenges such as "limited number of vaccine manufacturing companies (C2)" or "inappropriate coordination with local organizations (C13)". Among the cause group challenges, "long distance between vaccine stores and vaccination camps (C7)" can be given less importance because of its minor influence on other challenges. Among the effect group challenges, "vaccination cost and lack of financial support for vaccine purchase (C1)" stands out because of its high prominence vector (Di + Rj) value. Therefore, even though it is an effect group challenge, it must be handled with highest priority by the movers and shakers of COVID-19 VSC. Additionally, key challenges such as "difficulty of tracking vaccinated population (C12)" and "inadequate positive vaccine marketing (C5)" are also critical because of their high relation vector (Di - Rj) and prominence vector (Di + Rj) values.

Failure to overcome the identified challenges can have severe consequences, some of which have already been encountered by different countries. For instance, production delays and blood clot incidents of the AstraZeneca vaccine already caused severe disruption in vaccine rollout within the European Union (Wise, 2021). This is one of the direct impacts of the most significant challenge found by this study: the "limited number of vaccine manufacturing companies (C2)". Furthermore, by drawing comparison between vaccine strategies of the US and Israel, Freed (2021) demonstrates how critical the proper coordination between federal government and local level organizations is. Consistent with the findings of (Freed, 2021), this study ranks "inappropriate coordination with local organizations (C13)", as the second most significant challenge. Additionally, though "inadequate positive vaccine marketing (C5)" is a 6th ranked key challenge, it can contribute to vaccine hesitancy which in turn can act as a barrier to full population inoculation (Dror et al., 2020). This implies that managers in the COVID-19 VSC need to systematically overcome each challenge identified by this study for successful execution of vaccination of the full population of the world.

The current outbreak has greatly affected the economic, environmental, and social pillars of sustainability and jeopardized achievement of sustainable development goals (Ranjbari et al, 2021a, 2021b). Immunization plays a critical role in achieving 14 of the 17 SDGs because of its direct impact on poverty reduction, longer and healthier lives, women empowerment, and long-term stability of health systems (León et al., 2019). The proposed IF-DEMATEL framework to identify and classify the challenges of VSC can help policymakers to formulate flexible strategies for the vaccine distribution and minimize the negative impact on SDGs. Government of different countries can also analyze the interactions among these challenges for successful execution of their vaccination programs. Overcoming the 15 challenges related to COVID-19 VSC identified in this study will facilitate countries worldwide to reach herd immunity and quickly recover from economic and social losses caused by the pandemic.

Sustainable and flexible solutions such as investment in vaccine manufacturing companies can protect against increased inequality due to vaccine nationalism and thus facilitate achieving SGD 10 which is to reduce inequalities within and among countries. Such an investment will also facilitate achieving the goal of peace, justice, and strong institutions (SGD 16). Overcoming the challenge of lack of vaccine manufacturing companies (C2) will require active engagement of governments and vaccine manufacturers for improving the vaccine supply chain, and thus this can promote partnerships for the goal (SDG 17). Availability of more vaccine manufacturing companies will substantially reduce vaccination costs and will make vaccine more affordable to developing countries, which will help achieving the poverty reduction goal (SGD 1).

Investment in information technology for accurate demand forecasting and monitoring of vaccinated population can give rise to sustainable cities and communities (SGD 11). Such investment can also promote SGD 9, which relates to industry, innovation, and infrastructure by requiring supply chain-wide collaboration of VSC members to bring forward new innovative technologies to safeguard the vaccinated population against any non-vaccinated population. Overcoming the challenge of accurate vaccine demand forecast (C3) and monitoring of vaccinated population (C12) can facilitate decent work and economic growth (SGD 8) by bringing back the properly vaccinated part of the population to its work environment.

Additionally, getting over consumer unwillingness to vaccinate and setting up positive marketing campaigns for vaccines can ensure mass vaccination and thus contributing to SDG 3 which is good health and well-being of the general population. It can also facilitate quality education (SGD 4) by bringing pupils back to schools. Together, by taking care of all challenges can ensure zero hunger (SGD 2) by stopping the death of earning family members. Therefore, it is of utmost importance to carefully scrutinize these challenges and understand their implications. This study facilitates better comprehension of COVID-19 VSC challenges and thereby contributing to recovering faster from this pandemic.

6. Conclusions and future works

The COVID-19 pandemic has created an immense global crisis causing severe damage to the sustainability of the human race. Vaccines increase the chance of preventing the transmission of the disease and protect people's lives. Therefore, the need to vaccinate the entire population against the COVID-19 virus is not only pressing but also the most effective way to recover from the pandemic. Development, manufacturing, distribution, and administration of vaccines are challenging. The role of the VSC is to deliver the right vaccine in the right quantity to be delivered to the right place at the right time. Governments will be required to develop evidence-based strategies for ensuring that COVID-19 vaccines lead to widespread vaccination. This paper investigates and classifies challenges of the COVID-19 VSC in order to contribute to the fight against the global pandemic. Considering supply chain challenges long before a vaccine is administered to the general population can help design successful vaccination campaigns. Therefore, identification of key challenges to the COVID-19 VSC is customary for a sustainable VSC that could help the countries around the world to getting out of the pandemic.

In this paper, 15 challenges to the COVID-19 VSC were found in the literature and via VSC experts. These challenges are then classified using the IF-DEMATEL method. The IF-DEMATEL method classifies the challenges to cause and effect groups. Seven challenges are in the cause group whereas eight challenges are in the effect group. The highest-ranking challenge in the cause group is "Lack of vaccine monitoring bodies (C14)". In contrast, the top ranked in the effect group is "Consumers' unwillingness to vaccinate (C4)". This paper also ranks the challenges with regard to prominence vector and finds the top challenges to be 'Limited number of vaccine manufacturing companies (C2)'. To demonstrate the interrelationship among the challenges, this study also maps the challenges in the prominence-relation map where these challenges are categorized into four categories: key challenges, minor key challenges, independent challenges and indirect challenges. Such fine categorization of challenges will allow VSC members, governments, and policy makers to tackle these challenges in a resource efficient way. While all the challenges are important to consider, cause group challenges can be dealt with first. Among the cause group challenges, key challenges are the most significant ones and thereby needing significant attention of the governments worldwide for successful execution of VSC. This study also draws implications of the identified challenges on SGDs and demonstrates that at least 9 of the 17 SGDs are impacted.

Nonetheless, this study is not devoid of limitations. The limited number of experts used in this study creates opportunities for future studies of including a large number of stakeholders and decision- and policymakers. Furthermore, the study only applies one methodology (IF-DEMATEL) to categorize and rank the challenges. Therefore, future research can be directed to checking the validity, feasibility, reliability, and sensitivity of the findings of this research. Moreover, future studies can include more challenges from different stages of the VSC such as development, production, distribution, and administration. Additionally, the identified challenges listed are only reflecting experts' opinions from developing countries; thereby, the suitability of the results may be limited to low-and-middle income countries. Thus, further studies can be developed comprising experts from both developed and developing countries. In addition, future research could combine DEMATEL with Fuzzy Predictable User Experience Algorithm (FPUEA) and Hesitant Fuzzy sets with DEMATEL to form new methods. Finally, applying different MCDM approaches to prioritize issues, challenges, drivers, and barriers related to current pandemic can be explored in future studies.

Credit authorship statement

Shahriar Tanvir Alam: Conceptualization, Methodology, Software, Formal analysis, Resources, Writing - Original Draft, Review & Editing. **Sayem Ahmed:** Conceptualization, Methodology, Software, Formal analysis, Resources, Writing - Original Draft, Review & Editing. **Syed Mithun Ali:** Conceptualization, Methodology, Software, Resources, Writing - Review & Editing, Research Administration, Supervision. **Sudipa Sarker:** Visualization, Data Curation, Investigation, Resources, Writing - Review & Editing, Research Administration. **Golam Kabir:** Conceptualization, Methodology, Software, Resources, Writing - Review & Editing. **Md. Asif-Ul-Islam:** Writing - Review & Editing.

Appendix A

Table A1
The "Initial Direct-Relation Matrix" in IFS

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0,0	0.4,0	0.4,0	0.2,0.1	0.1,0.1	0.2,0.1	0.05,0.2	0.05,0.1	0.05,0.2	0.2,0.1	0.3,0	0.2,0.1	0.3,0	0.2,0	0.3,0.2
C2	0.8,0	0,0	0.3,0	**0.3,0.1**	0.2,0.1	0.6,0.2	0.1,0.5	0.2,0.1	0.1,0.3	0.5,0.2	0.8,0	0.4,0	0.8,0	1,0	0.5,0.2
C3	0.4,0	0.8,0	0,0	0,0.1	0,0.1	0,0.2	0.1,0.2	0.3,0.05	0,0.1	0,0.1	0,0	0,0	0.2,0	0,0	0.3,0
C4	0.2,0.5	0.5,0.4	0.1,0.2	0,0	0.2,0	0.2,0	0.2,0	0.1,0	0.1,0.1	0.2,0	0,0	0.05,0.1	0.3,0	0,0.5	0,0.4
C5	0.1,0.1	0.6,0.1	0,0.1	0.05,0.05	0,0	0,0	0,0	0,0	0,0.05	0,0	0.05,0	0,0	0.1,0	0.05,0.2	0.3,0.1
C6	0.3,0.3	0,0.6	0.2,0.1	0.1,0	0,0	0,0	0.2,0	0.1,0	0.4,0.1	0.05,0	0,0.1	0,0.2	0,0	0,0.8	0,0.6
C7	0.1,0.2	0.05,0.4	0,0.1	0.2,0	0,0	0.5,0	0,0	0.1,0	0.3,0.2	0.4,0.1	0,0.1	0,0.05	0,0	0,0.8	0.2,0.5
C8	0.1,0.1	0.2,0.3	0,0	0.1,0	0,0	0,0	0.1,0	0,0	0.5,0.05	0,0.05	0.05,0.1	0,0.4	0,0	0.2,0.4	0.4,0.1
C9	0.4,0.6	0.5,0.5	0.6,0.4	0.4,0.6	0.6,0.4	0.6,0.4	0.4,0.6	0.6,0.3	0,0	0.7,0.3	0.4,0.6	0,0	0,0	0.5,0.5	0.6,0.4
C10	0.1,0.3	0.2,0.4	0,0	0.3,0	0,0	0.1,0	0.1,0	0,0	0.1,0	0,0	0,0.2	0,0.1	0,0	0.05,0.2	0.05,0.1
C11	1,0	0.8,0	0.2,0	0.2,0.2	0,0	0,0.6	0,0.2	0,0.1	0.7,0	0,0.3	0,0	0.6,0	0,0	1,0	0.6,0
C12	0.7,0.2	0.8,0.1	0.1,0	0.3,0.2	0,0.1	0.05,0.4	0.1,0.3	0,0.2	0,0	0,0.2	0.8,0	0,0	0,0	0.6,0.05	0.5,0.05
C13	0.7,0	0.7,0	0.4,0	0.4,0	0.01,0.05	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,0	0.3,0
C14	0.8,0	1,0	0.3,0	0,0.6	0,0.1	0,0.6	0,0.6	0.2,0.1	0.6,0.1	0,0.2	0.8,0	0.8,0	0.9,0	0,0	0.5,0
C15	0.6,0.2	0.5,0	0.3,0.1	0,0.3	0.05,0.1	0,0.6	0.2,0.4	0.4,0.3	0.5,0.1	0.05,0.3	0,0	0,0	0.5,0	0.6,0.1	0,0

Table A2
The "Initial Direct-Relation Matrix" in standard fuzzy subset

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.000	0.700	0.700	0.550	0.500	0.550	0.425	0.475	0.425	0.550	0.650	0.550	0.650	0.600	0.550
C2	0.900	0.000	0.650	**0.600**	0.550	0.700	0.300	0.550	0.400	0.650	0.900	0.700	0.900	1.000	0.650
C3	0.700	0.900	0.000	0.450	0.450	0.400	0.450	0.625	0.450	0.450	0.500	0.500	0.600	0.500	0.650
C4	0.350	0.550	0.450	0.000	0.600	0.600	0.600	0.550	0.500	0.600	0.500	0.475	0.650	0.250	0.300
C5	0.500	0.750	0.450	0.500	0.000	0.500	0.500	0.500	0.475	0.500	0.525	0.500	0.550	0.425	0.600
C6	0.500	0.200	0.550	0.550	0.500	0.000	0.600	0.550	0.650	0.525	0.450	0.400	0.500	0.100	0.200
C7	0.450	0.325	0.450	0.600	0.500	0.750	0.000	0.550	0.550	0.650	0.450	0.475	0.500	0.100	0.350
C8	0.500	0.450	0.500	0.550	0.500	0.500	0.550	0.000	0.725	0.475	0.475	0.300	0.500	0.400	0.650
C9	0.400	0.500	0.600	0.400	0.600	0.600	0.400	0.650	0.000	0.700	0.400	0.500	0.500	0.500	0.600
C10	0.400	0.400	0.500	0.650	0.500	0.550	0.550	0.500	0.550	0.000	0.400	0.450	0.500	0.425	0.475
C11	1.000	0.900	0.600	0.500	0.500	0.200	0.400	0.450	0.850	0.350	0.000	0.800	0.500	1.000	0.800
C12	0.750	0.850	0.550	0.550	0.450	0.325	0.400	0.400	0.500	0.400	0.900	0.000	0.500	0.775	0.725
C13	0.850	0.850	0.700	0.700	0.480	0.500	0.500	0.500	0.500	0.500	0.500	0.500	0.000	1.000	0.650
C14	0.900	1.000	0.650	0.200	0.450	0.200	0.200	0.550	0.750	0.400	0.900	0.900	0.950	0.000	0.750
C15	0.700	0.750	0.600	0.350	0.475	0.200	0.400	0.550	0.750	0.375	0.500	0.500	0.750	0.750	0.000

Table A3
The "Initial Direct-Relation Matrix" in crisp values

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0	2.8	2.8	2.2	2	2.2	1.7	1.9	1.7	2.2	2.6	2.2	2.6	2.4	2.2
C2	3.6	0	2.6	**2.4**	2.2	2.8	1.2	2.2	1.6	2.6	3.6	2.8	3.6	4	2.6
C3	2.8	3.6	0	1.8	1.8	1.6	1.8	2.5	1.8	1.8	2	2	2.4	2	2.6
C4	1.4	2.2	1.8	0	2.4	2.4	2.4	2.2	2	2.4	2	1.9	2.6	1	1.2
C5	2	3	1.8	2	0	2	2	2	1.9	2	2.1	2	2.2	1.7	2.4
C6	2	0.8	2.2	2.2	2	0	2.4	2.2	2.6	2.1	1.8	1.6	2	0.4	0.8
C7	1.8	1.3	1.8	2.4	2	3	0	2.2	2.2	2.6	1.8	1.9	2	0.4	1.4
C8	2	1.8	2	2.2	2	2	2.2	0	2.9	1.9	1.9	1.2	2	1.6	2.6
C9	1.6	2	2.4	1.6	2.4	2.4	1.6	2.6	0	2.8	1.6	2	2	2	2.4
C10	1.6	1.6	2	2.6	2	2.2	2.2	2	2.2	0	1.6	1.8	2	1.7	1.9
C11	4	3.6	2.4	2	2	0.8	1.6	1.8	3.4	1.4	0	3.2	2	4	3.2
C12	3	3.4	2.2	2.2	1.8	1.3	1.6	1.6	2	1.6	3.6	0	2	3.1	2.9
C13	3.4	3.4	2.8	2.8	1.92	2	2	2	2	2	2	2	0	4	2.6
C14	3.6	4	2.6	0.8	1.8	0.8	0.8	2.2	3	1.6	3.6	3.6	3.8	0	3
C15	2.8	3	2.4	1.4	1.9	0.8	1.6	2.2	2.8	1.5	2	2	3	3	0

Table A4
The "Normalized Direct-Relation Matrix"

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.0000	0.0741	0.0741	0.0582	0.0529	0.0582	0.0450	0.0503	0.0450	0.0582	0.0688	0.0582	0.0688	0.0635	0.0582
C2	0.0952	0.0000	0.0688	0.0635	0.0582	0.0741	0.0317	0.0582	0.0423	0.0688	0.0952	0.0741	0.0952	0.1058	0.0688
C3	0.0741	0.0952	0.0000	0.0476	0.0476	0.0423	0.0476	0.0661	0.0476	0.0476	0.0529	0.0529	0.0635	0.0529	0.0688
C4	0.0370	0.0582	0.0476	0.0000	0.0635	0.0635	0.0635	0.0582	0.0529	0.0635	0.0529	0.0503	0.0688	0.0265	0.0317
C5	0.0529	0.0794	0.0476	0.0529	0.0000	0.0529	0.0529	0.0529	0.0503	0.0529	0.0556	0.0529	0.0582	0.0450	0.0635
C6	0.0529	0.0212	0.0582	0.0582	0.0529	0.0000	0.0635	0.0582	0.0688	0.0556	0.0476	0.0423	0.0529	0.0106	0.0212
C7	0.0476	0.0344	0.0476	0.0635	0.0529	0.0794	0.0000	0.0582	0.0582	0.0688	0.0476	0.0503	0.0529	0.0106	0.0370
C8	0.0529	0.0476	0.0529	0.0582	0.0529	0.0529	0.0582	0.0000	0.0767	0.0503	0.0503	0.0317	0.0529	0.0423	0.0688
C9	0.0423	0.0529	0.0635	0.0423	0.0635	0.0635	0.0423	0.0688	0.0000	0.0741	0.0423	0.0529	0.0529	0.0529	0.0635
C10	0.0423	0.0423	0.0529	0.0688	0.0529	0.0582	0.0582	0.0529	0.0582	0.0000	0.0423	0.0476	0.0529	0.0450	0.0503
C11	0.1058	0.0952	0.0635	0.0529	0.0529	0.0212	0.0423	0.0476	0.0899	0.0370	0.0000	0.0847	0.0529	0.1058	0.0847
C12	0.0794	0.0899	0.0582	0.0582	0.0476	0.0344	0.0423	0.0423	0.0529	0.0423	0.0952	0.0000	0.0529	0.0820	0.0767
C13	0.0899	0.0899	0.0741	0.0741	0.0508	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0529	0.0000	0.1058	0.0688
C14	0.0952	0.1058	0.0688	0.0212	0.0476	0.0212	0.0212	0.0582	0.0794	0.0423	0.0952	0.0952	0.1005	0.0000	0.0794
C15	0.0741	0.0794	0.0635	0.0370	0.0503	0.0212	0.0423	0.0582	0.0741	0.0397	0.0529	0.0529	0.0794	0.0794	0.0000

Table A5
The "Total-Relation Matrix"

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C1	0.3046	0.3807	0.3398	0.2962	0.2886	0.2761	0.2535	0.2973	0.3116	0.2949	0.3393	0.3134	0.3548	0.3350	0.3273
C2	0.4537	0.3748	0.3890	0.3474	0.3397	0.3315	0.2823	0.3526	0.3629	0.3502	0.4178	0.3794	0.4356	0.4282	0.3911
C3	0.3657	0.3907	0.2639	0.2806	0.2777	0.2570	0.2500	0.3050	0.3064	0.2797	0.3185	0.3015	0.3431	0.3193	0.3299
C4	0.2995	0.3238	0.2811	0.2126	0.2687	0.2557	0.2457	0.2733	0.2847	0.2709	0.2884	0.2717	0.3161	0.2639	0.2675

(continued on next page)

Table A5 (*continued*)

Challenges	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
C5	0.3305	0.3599	0.2952	0.2734	0.2204	0.2555	0.2449	0.2806	0.2956	0.2725	0.3061	0.2881	0.3229	0.2967	0.3105
C6	0.2829	0.2607	0.2647	0.2446	0.2368	0.1753	0.2264	0.2500	0.2733	0.2414	0.2561	0.2391	0.2732	0.2214	0.2317
C7	0.2931	0.2867	0.2684	0.2614	0.2485	0.2600	0.1772	0.2620	0.2773	0.2648	0.2697	0.2587	0.2876	0.2348	0.2585
C8	0.3174	0.3192	0.2898	0.2688	0.2623	0.2478	0.2427	0.2220	0.3100	0.2619	0.2892	0.2589	0.3067	0.2817	0.3045
C9	0.3189	0.3350	0.3083	0.2630	0.2794	0.2640	0.2355	0.2946	0.2476	0.2906	0.2924	0.2864	0.3166	0.3009	0.3097
C10	0.2987	0.3052	0.2814	0.2717	0.2552	0.2462	0.2369	0.2646	0.2852	0.2068	0.2745	0.2653	0.2979	0.2750	0.2794
C11	0.4442	0.4444	0.3680	0.3215	0.3206	0.2715	0.2766	0.3284	0.3873	0.3083	0.3150	0.3739	0.3820	0.4129	0.3900
C12	0.3927	0.4095	0.3372	0.3044	0.2934	0.2621	0.2577	0.2998	0.3300	0.2898	0.3758	0.2709	0.3538	0.3658	0.3564
C13	0.4203	0.4286	0.3692	0.3348	0.3122	0.2951	0.2820	0.3266	0.3470	0.3162	0.3560	0.3373	0.3233	0.4014	0.3658
C14	0.4393	0.4569	0.3751	0.2965	0.3170	0.2722	0.2593	0.3387	0.3796	0.3137	0.4042	0.3845	0.4246	0.3224	0.3887
C15	0.3684	0.3808	0.3258	0.2713	0.2813	0.2383	0.2453	0.2995	0.3316	0.2737	0.3206	0.3041	0.3593	0.3460	0.2687

Appendix B

Questionnaire

The spread of COVID-19 has prompted significant disbalance in all parts of the globe. COVID-19 pandemic has influenced the whole world, from developing countries to developed countries. Appropriate vaccine development is not only the solution to the current severe situation; proper distribution of it plays a significant role. A pandemic vaccine supply chain (VSC) is different from that of a traditional VSC, and COVID-19 VSC is the most important topic at this present time. Several challenges for COVID-19 VSC are pointed out in the initial stage.

The reason for the survey is to identify and focus on the COVID-19 VSC challenges to conquer the identified challenges dependent on your input. Your feedback will be kept secret and would be utilized stringently for research purposes. The survey needs approximately 15 min to finish. We value your involvement and thank you for your assistance.

Please identify significant challenges that can be the most important for this COVID-19 VSC.

A list of challenges that identified from extant literature is provided with this email. You can add or delete any challenge based on your experience.

Table B1
List of challenges of vaccine supply chain identified from extant literature

Serial No.	Challenges of VSC
1	Limited number of vaccine manufacturing companies
2	Lack of accurate vaccine demand forecast
3	Consumers' unwillingness to vaccinate
4	Unavailability of volunteers for vaccine trials
5	Long distance between vaccine stores and vaccination camps
6	Lack of proper planning and scheduling
7	Lack of proper storage systems
8	Difficulties in monitoring and controlling vaccine temperature
9	Difficulty of tracking vaccinated population
10	Lack of correspondence between the VSC members
11	Immunization program delivery strategies
12	Topographical boundaries

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