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COVID-19 Vaccine: A neutrosophic MCDM approach for determining the priority groups

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ABSTRACT

Since the outbreak of COVID-19, most of the countries around the world have been confronting the loss of lives, struggling with several economical parameters, i.e. low GDP growth, increasing unemployment rate, and others. It's been 11 months since we are struggling with COVID-19 and some of the countries already facing the second wave of COVID-19. To get rid of these problems, inventions of a vaccine and its optimum distribution is a key factor. Many companies are trying to find a vaccine, but for nearly 8 billion people it would be impossible to find a vaccine. Thus, the competition arises, and this competition would be too intense to satisfy all the people of a country with the vaccine. Therefore, at first, governments must identify priority groups for allocating COVID-19 vaccine doses. In this work, we identify four main criteria and fifteen sub-criteria based on age, health status, a woman's status, and the kind of job. The main and sub-criteria will be evaluated using a neutrosophic Analytic Hierarchy Process (AHP). Then, the COVID-19 vaccine alternatives will be ranked using a neutrosophic TOPSIS method. All the results obtained indicate that the healthcare personnel, people with high-risk health, elderly people, essential workers, pregnant and lactating mothers are the most prioritized people to take the vaccine dose first. Also, the results indicate that the most appropriate vaccine for patients and health workers have priority over other alternative vaccines.

Introduction

The world is facing uncountable challenges regarding the COVID-19 vaccine, the most important of challenges are: no vaccine has been approved when we are conducting this study. The available doses will be so limited, especially in the current period, so the doses will not meet the needs. The optimum allocation of vaccines globally and locally is another challenge. The challenges of supply, storage, and delivery of vaccines must take place under strict sanitary conditions is unavoidable too. It is also difficult to reach some remote areas or minorities due to the unavailability of storage requirements and safe delivery..

Recently, a few reports have emerged that set a standard framework for allocating the vaccines, the most important of which is done by a strategic advisory group of experts on immunization of WHO [1]. This advisory committee intends to provide a valuable framework guide related to allocating vaccines at global, national, and regional levels, especially when there will be a scarcity of vaccines or limited supply. They have identified six lofty goals for vaccines, which are: First, the well-being of human beings, ensuring the preservation of humans' life, reducing the number of deaths, continuing basic and health services, and preserving the economic and social sectors. Secondly, equality, justice, and respect for the interests of all individuals and groups during the allocation considering the criteria for setting priorities. Third, globally equality, allocating the vaccine according to the needs and pandemic risk of each country, regardless of gender, color, or per capita income, and helping countries that are unable to provide the vaccine to their citizens. Fourth: locally Equality; achieving fairness of allocation for all segments of society, its sects and town, especially minorities, socially disadvantaged groups, and residents of rural and remote areas, while giving precedence to groups of priority. Fifthly, working to protect those who work on the front lines in facing the virus, such as health workers, as well as those working in basic areas to protect the welfare of others. Sixth: Legitimacy: Working to involve experts, scientists, and stakeholders in determining the scientific, health, and value standards to

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Table 1
Random Index by Saaty [4].

Matrix size	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

be used in making privatization decisions and to determine priorities groups on the global and local levels.

Dooling K. [2] divided segments of society into two levels: In the first level, priority is given to health care employees, people who have high health risks, old people, and essential workers to provide services to people. In the second level, the priority is given to the secondary-line workers who support health-care workers and people who face greater barriers to accessing care if they become seriously ill or whose living or working conditions put them at risk of infection, even if they have a lower or unknown risk of serious illness and death. Moreover, the workgroup also proposed guidelines, the most important of which are the safety and following comprehensive clinical trials to ensure the effectiveness of the vaccine before generalization, and the effective and equitable allocating, as well as flexibility in allocation based on the size of the epidemic and the demand.

Bubar KM et al. [3] used an informed approach to prioritize vaccines based on age and serological status. They concluded that to reduce the cumulative infection, priority should be given for adults aged between 20 and 49 years, and to reduce the mortality rate, priority should be given for adults over the age of 60 years.

Based on the above-mention studies a vivid statement can be concluded that there are several groups of people that should consider while giving priority above one another. To identify the effective allocation of the COVID-19 vaccine for priority groups, decision-makers must involve experts from multiple fields to get benefit from their experiences in setting priorities and principle guidelines. When there are several alternatives and priorities the Multiple-Criteria Decision-Making (MCDM) approach can play a vital role to determine and choose the best alternatives. One of the common approaches used to determine and choose the best alternatives is MCDM approach . There are many improved MCDM methods and the three most common methods are Analytic Hierarchy Process (AHP) [4], VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method [5], and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [6].

Besides, many studies applied MCDM methods in real application. One interesting application of MCDM methods in vaccine selection is the study presented by Daphne Lopez and M. Gunasekaran 2015 [7] where they applied the fuzzy VIKOR approach to evaluate H1N1 Influenza vaccination strategies. The other interesting study presented by Singh R, and Avikal S.in 2020 [8] used the AHP method to identify preventive activities prioritization to curb the COVID-19 outbreak. Similar work in [9], the authors used AHP and VIKOR approach to determine the prioritization of patients with COVID-19 based on their health conditions. On the other hand, Since the past decade, the concept of neutrosophic is being used in special cases where data are ambiguous and uncertain. The neutrosophic, like other fields, contributed to the understanding and analyzing COVID-19 pandemic too. In this regard, the authors in [10] reviewed the challenges and potentialities of deep transfer learning and edge computing to contribute to curbing the COVID-19 pandemic. While the authors in [11] inserted the neutrosophic concept on the deep transfer learning model where four types of images are considered, the original images, the True (T) neutrosophic images, the Indeterminacy (I) neutrosophic images, and the Falsity (F) neutrosophic images. The authors in [12] utilized the m-polar neutrosophic number (MPNNs) in the generalized weighted aggregation and generalized Einstein weighted aggregation operators for the diagnosis of COVID-19 and examination. Besides, the authors in [13] proposed Health-Fog framework universal system to mitigate the COVID-19 pandemic in terms of diagnosis, treatment, and prevention.

To the best of the authors' knowledge, this is the first work to

Table 2
Main criteria and sub-criteria descriptions.

Age index AC (C_1)	
• **Old people with health problem OWH** (c_{11})	This group refers to the old people where their age is more than 60 years and they have some health problems.
• **Old people without health problem OUH** (c_{12})	It indicates to the elderly but in good health.
• **Adult people with health problem AWH** (c_{13})	This category refers to the age group between 18 to less than 60. Besides, it is assumed that they suffer from health problems such as lack of immunity, diabetes, pressure, and other diseases that may cause death if a person is infected with COVID-19.
• **Adults people without health problem AUH** (c_{14})	It refers to young people in good health condition.
• **Kids with health problem KWH** (c_{15})	The age of this group is less than 18 years, moreover, the kids suffer from health problems.
• **Kids without health problem KUH** (c_{16})	It indicates to the kids in good health
Health state index HS (C_2)	
• **For people with high-risk health problems PHR** (c_{21})	It refers to individuals who have serious diseases related to immune deficiency, diabetes, allergies, kidney failure, heart, and other very serious diseases that lead to death, especially if infection coincides with COVID-19 infection. This group with medical conditions is more likely to contract a severe COVID-19 virus, so they are classified as an independent group.
• **People with health problems PWH** (c_{22})	It refers to the individuals having health problems but not serious diseases.
• **Healthy people PUH** (c_{23})	It indicates the individuals in good health condition.
Women state index WC (C_3)	
• **Pregnant WP** (c_{31})	During the pregnancy, the women usually have a weak immunity system and are susceptible to disease, so pregnant women have been classified as a community group that has priority to take the COVID-19 vaccine over others.
• **Lactating women WL** (c_{32})	It points to breastfeeding women and has priority because being infected with the COVID-19 virus will have serious complications for her and her infant kid.
• **Others women WO** (c_{33})	It refers to other women who are not pregnant or breastfeeding.
Job kind index JK (C_4)	
• **Health workers HP** (c_{41})	All individuals working in health care places who have direct or indirect exposure to patients or infectious materials as well as people who are not directly involved in patient care but who may be exposed to infectious agents while working in a health care environment, Such as doctors, nurses, lab technicians, and administrative staff. Health workers are the first line of defense to fight the COVID-19 virus. And preserving their lives have priority so that they can continue to provide their medical services. Therefore, they were classified as an independent group.
• **Essential workers EW** (c_{42})	This class is so important for the life continuity and maintenance of basic services, such as workers in logistics, supply, agriculture, transport, education, hygiene, energy, security, armed forces, and the judiciary. But priority should be given to those who cannot work remotely more than others.
• **Others workers OS** (c_{43})	It indicates to the workers in the other sectors.

prioritize the groups for allocating the COVID-19 vaccine through the neutrosophic MCDM approach. The process of the neutrosophic MCDM approach is as follows:

- In this approach at first, we must identify four main-criteria and fifteen sub-criteria, and afterward, the two MCDM techniques are applied namely AHP and TOPSIS.
- Then neutrosophic AHP is employed to determine the weights of both main criteria and sub-criteria
- The obtained weights are used to rank the main criteria and rank sub-criteria within its main criteria.
- Then, TOPSIS is used to evaluate the COVID-19 vaccine alternatives to select a suitable vaccine in the early stage.

The rest of this research is organized as follows: Section 2 introduces the brief of the used theoretical part of this work. Section 3 reports the main and sub-criteria, as well as COVID-19 vaccine alternatives. Section 4 presents the proposed approach based on neutrosophic AHP and TOPSIS methods. In Section 5, the results and discussions are reported. Finally, the conclusion and suggestions for future work are presented in Section 6.

Theory

Analytic hierarchy process (AHP)

AHP is one of the most common MCDM methods proposed by Saaty T. (1980) [4]. This method has wide applications in many areas, especially the health sector, which contributes to determining the priorities between the main and sub-criteria, as well as ranking the available alternatives during the decision-making process, which give highlight for decision-makers to make the optimal decision.

The steps of AHP methods are as follows:

Step 1. Identify the main criteria, sub-criteria, and alternatives

Step 2. Construct pairwise comparisons of the criteria and comparisons of alternatives for each criterion.

Step 3. Calculate the priority matrix and the criteria weights.

Step 4. Calculate the consistency ratio (CR) using Eq. (1) to straighten the consistency of comparison. The consistency is suitable if CR is less than 0, and inconsistent otherwise. In this case, comparison components have to be adjusted for superior consistency.

$$CR = \frac{CI}{RI} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

Where λ_{max}, is the mean of the weighted sum vector divided by the corresponding criteria, and n is the number of criteria. And RI is a random index reported in Table 1.

Step 5. Analysis of the AHP scores, and select the best alternative if the model is consistent. Table 2

Topsis

TOPSIS is another common MCDM method proposed by Hwang and Yoon 1981 [6]. It contributes to the comparison and ranking of alternatives. The main steps of TOPSIS are as follows:

Let there is m of the criteria and n of alternatives, let $\left[p_{ij}\right]_{n\times m}$ be the matrix of the decision-making

Step 1. Construct the decision matrix where the dimension of this matrix are the criteria and the alternatives

Step 2. Normalize the decision matrix, then obtain the weighted normalized matrix using the equation (3):

$$WM = (p_{ij})_{m\times n} = w_j \times p_{ij} \tag{3}$$

where i refers to the substitutes, j refers to the criteria.

Step 3. Identify the positive and negative ideal solution using Eqs. (4) and (5).

$$A^{+} = \left\{ \left(\max_{j} p_{ij} | j\in J \right) | i = 1, \cdots, m \right\} \tag{4}$$

$$A^{-} = \left\{ \left(\min_{j} p_{ij} | j\in J \right) | i = 1, \cdots, m \right\} \tag{5}$$

Step 4. Calculate the Euclidean distance between the positive perfect solution ds_i^+ and negative perfect solution ds_i^- using Eqs. (6) and (7).

$$ds_i^{+} = \sqrt{\sum_{j=1}^{n} (p_{ij} - p_i^{+})^2}, \quad \mathrm{i} = 1, 2, \cdots, m \tag{6}$$

$$ds_i^{-} = \sqrt{\sum_{j=1}^{n} (p_{ij} - p_i^{-})^2}, \quad \mathrm{i} = 1, 2, \cdots, m \tag{7}$$

Step 5. Compute the proportional closeness to the positive perfect solution for each alternative using (8).

$$PS_i = \frac{ds_i^-}{ds_i^+ + ds_i^-}, \quad \mathrm{i} = 1, 2, \cdots, m \tag{8}$$

Based on the results of PS_i rank the alternatives where the highest value is the superior alternative.

Neutrosophic

Smarandache 1998 [14] is the pioneer of neutrosophic logic which is extended the intuitionistic fuzzy set (Atanassov (1986) [15]). The intuitionistic fuzzy is also generalized to the fuzzy theory (Zadeh 1965 [16]) where it deals with uncertainty. On the other hand, in real applications, the parameter inputs are not crisp. Rather, uncertainty inputs are dealt with, hence the importance of using fuzzy and neutrosophic is inevitable in real-life cases.

Definition 1. *Let $X \neq \varnothing$ be a universal set. A neutrosophic set AinX is characterized by a truth-membership function $\mu_{\underset{A}{\sim}^N}$, an indeterminacy-membership function $\sigma_{\underset{A}{\sim}^N}$, and a falsity-membership function $\nu_{\underset{A}{\sim}^N}$:*

$$\widetilde{A}^N = \left\{ \left\langle x, \mu_{\underset{A}{\sim}^N}(x), \sigma_{\underset{A}{\sim}^N}(x), \upsilon_{\underset{A}{\sim}^N}(x) \right\rangle; x \in X \right\} \tag{9}$$

where $\mu_{\underset{A}{\sim}^N} : X \rightarrow]0^-, 1^+[$, $\sigma_{\underset{A}{\sim}^N} : X \rightarrow]0^-, 1^+[$, and $\upsilon_{\underset{A}{\sim}^N} : X \rightarrow]0^-, 1^+[$ represent the degrees of the truth-, indeterminacy-, and falsity-membership functions, respectively. No restriction exists on the sum of $\mu_{\underset{A}{\sim}^N}$,$\sigma_{\underset{A}{\sim}^N}$, and $\nu_{\underset{A}{\sim}^N}$. Thus, $0^- \leq \mu_{\underset{A}{\sim}^N}(x) + \sigma_{\underset{A}{\sim}^N}(x) + \nu_{\underset{A}{\sim}^N}(x) \leq 3^+$ for $x \in X$

Definition 2. *$((\alpha, \beta, \gamma) - cuts)$a set $(\alpha, \beta, \gamma) - cuts$, generated by $\widetilde{A}^N$, where $\alpha, \beta, \gamma \in [0, 1]$ are a fixed number such that $\alpha + \beta + \gamma \leq 3$ is defined as:*

$$\widetilde{A}^N_{\alpha,\beta,\gamma} = \left\{ \langle x, \mu_{\underset{A}{\sim}^N}(x), \sigma_{\underset{A}{\sim}^N}(x), \upsilon_{\underset{A}{\sim}^N}(x) \rangle; x \in X \mu_{\underset{A}{\sim}^N}(x) \geq \alpha, \sigma_{\underset{A}{\sim}^N}(x) \leq \beta, \upsilon_{\underset{A}{\sim}^N}(x) \leq \gamma; \alpha, \beta, \gamma \in [0, 1] \right. \tag{10}$$

where $(\alpha, \beta, \gamma) - cuts$, denoted by $\widetilde{A}^N_{\alpha,\beta,\gamma}$, is defined as the crisp set of elements x that belong to $\widetilde{A}^N$ at least to the degree α and that belongs to $\widetilde{A}^N$ at most to the degree βandγ.

Definition 3. *A generalized triangular neutrosophic number (GTNN) $\widetilde{\tau}_a^N = \langle (a, l_\mu, r_\mu; w_a), (a, l_\sigma, r_\sigma; u_a), (a, l_\nu, r_\nu; y_a) \rangle$ is a special neutrosophic set on a*

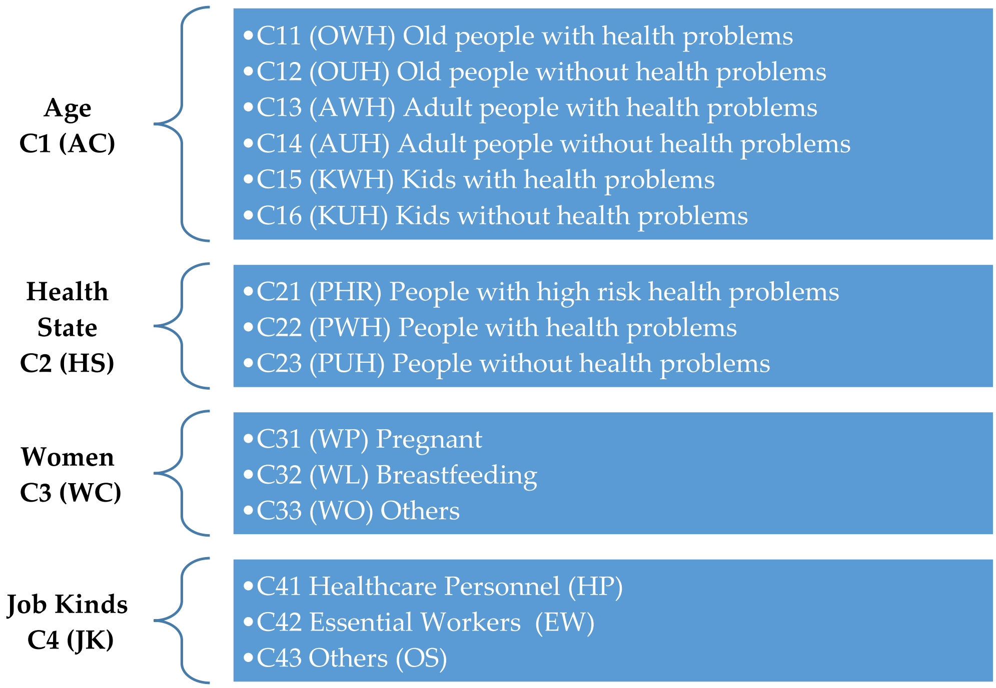

Fig. 1. Main criteria, and sub-criteria used in this study.

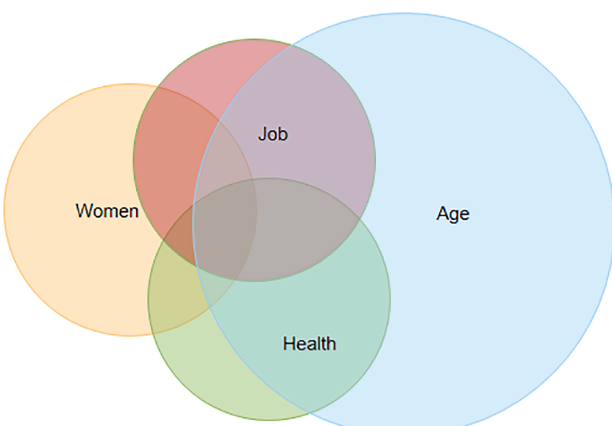

Fig. 2. Main groups overlapping.

real number set $\Re$ whose degree of truth-, indeterminacy-, and falsity- are given by:

$$\mu_{\tilde{\tau}_a^N}(x) = \begin{cases} \dfrac{x-a+l_\mu}{l_\mu} & a-l_\mu \le x < a \\ w_a & x = a \\ \dfrac{a+r_\mu-x}{r_\mu} & a < x \le a+r_\mu \\ 0 & otherwise \end{cases} \tag{11}$$

$$\sigma_{\tilde{\tau}_a^N}(x) = \begin{cases} \dfrac{(a-x)+u_a(x-a+l_\sigma)}{l_\sigma} & a-l_\sigma \le x < a \\ u_a & x = a \\ \dfrac{(x-a)+u_a(a+r_\sigma-x)}{r_\sigma} & a < x \le a+r_\sigma \\ 1 & otherwise \end{cases} \tag{12}$$

Table 3
Linguistic variables used for weighting the main criteria and sub-criteria.

Linguistic variables	Triangular neutrosophic scale $\langle(\mathbf{L},\mathbf{M},\mathbf{U});\mathbf{T},\mathbf{I},\mathbf{F}\rangle$
Low priority (LP)	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$
Simple Priority (SP)	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$
Medium priority (MP)	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$
High priority (HP)	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
Extremely priority (EP)	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$

Table 4
Evaluation of main criteria by three experts using linguistic variables.

Expert 1	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	–	1/ SP	MP	1/LP
C_2(HS)	SP	–	MP	1/LP
C_3(WC)	1/MP	1/MP	–	1/MP
C_4(JK)	LP	LP	MP	–
Expert 2	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	–	1/LP	SP	1/LP
C_2(HS)	LP	–	SP	1
C_3(WC)	1/SP	1/SP	–	1/LP
C_4(JK)	LP	1	LP	–
Expert 3	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	–	1/LP	LP	1/SP
C_2(HS)	LP	–	MP	LP
C_3(WC)	1/LP	1/MP	–	1/SP
C_4(JK)	SP	1/LP	SP	–

Table 5
Evaluation of main criteria by three experts using neutrosophic scale.

Expert 1	C_1(AC)	C_2(HS)	C_3(WC)	C_4(JK)
C_1(AC)	1	$1/\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$
C_2(HS)	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	1	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$
C_3(WC)	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	1	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$
C_4(JK)	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	1
Expert 2	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	1	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$
C_2(HS)	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	1	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	1
C_3(WC)	$1/\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	$1/\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	1	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$
C_4(JK)	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	1	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	1
Expert 3	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	1	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$1/\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$
C_2(HS)	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	1	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$
C_3(WC)	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	1	$1/\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$
C_4(JK)	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	1

Table 6
De-neutrosophiction for evaluation of main criteria by three experts.

Expert 1	C_1(AC)	C_2(HS)	C_3(WC)	C_4(JK)
C_1(AC)	1	0.3419	4.8750	0.9877
C_2(HS)	2.9250	1	4.8750	0.9877
C_3(WC)	0.2051	0.2051	1	0.2051
C_4(JK)	1.0125	1.0125	4.8750	1
Expert 2	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	1	0.9877	2.9250	0.9877
C_2(HS)	1.0125	1	2.9250	1
C_3(WC)	0.3419	0.3419	1	0.9877
C_4(JK)	1.0125	1	1.0125	1
Expert 3	**C_1(AC)**	**C_2(HS)**	**C_3(WC)**	**C_4(JK)**
C_1(AC)	1	0.9877	1.0125	0.3419
C_2(HS)	1.0125	1	4.8750	1.0125
C_3(WC)	0.9877	0.2051	1	0.3419
C_4(JK)	2.9250	0.9877	2.9250	1

$$\nu_{\tilde{\tau}_a^N}(x)=\begin{cases}\dfrac{(a-x)+y_a(x-a+l_\nu)}{l_\nu} & a-l_\nu\leq x<a\\ y_a & x=a\\ \dfrac{(x-a)+y_a(a+r_\nu-x)}{r_\nu} & a<x\leq a+r_\nu\\ 1 & otherwise\end{cases} \tag{13}$$

where l_μ, r_μ, l_σ, r_σ,l_ν, and r_ν are called the spreads of the truth-, indeterminacy-, and falsity-membership functions, respectively; and a is the mean value. w_a represents the maximum degree of the truth-membership function, while $u_a$and y_a represent the minimum degrees of the indeterminacy- and falsity-membership functions, respectively, such that they satisfy the conditions below:

$$0\leq w_a\leq 1, 0\leq u_a\leq 1, 0\leq y_a\leq 1 \text{ and } 0\leq w_a+u_a+y_a\leq 3. \tag{14}$$

In this work, we will use Eq. (15) for the de-neutrosophic and gotten the crisp values of neutrosophic numbers.

$$SC(x)=\frac{1}{8}\times(L+M+U)\times\left(2+\mu_{\tilde{A}^N}(x)-\sigma_{\tilde{A}^N}(x)-\upsilon_{\tilde{A}^N}(x)\right) \tag{15}$$

Table 7
Final weights of main criteria by three experts.

Criteria	Summation of weights	Final weights by Expert 1	Summation of weights	Final weights by Expert 2	Summation of weights	Final weights by Expert 3	Final weights	Rank
C_1(AC)	0.9506	0.2376	1.2141	0.3035	0.7093	0.1773	0.2395	3
C_2(HS)	1.5820	0.3955	1.2246	0.3062	1.3576	0.3394	0.3470	1
C_3(WC)	0.2485	0.0621	0.5799	0.1450	0.4599	0.1150	0.1074	4
C_4(JK)	1.2189	0.3047	0.9814	0.2453	1.4732	0.3683	0.3061	2

Table 8
Evaluation of the sub-criteria of age index by three experts using linguistic variables.

Three experts	Age index (C_1)					
	c_{11}(OWH)	c_{12}(OUH)	c_{13}(YWH)	c_{14}(YUH)	c_{15}(KWH)	c_{16}(KUH)
c_{11}(OWH)	1	MP	LP	EP	LP	EP
c_{12}(OUH)	1/ MP	1	1/MP	MP	1/HP	HP
c_{13}(YWH)	1/LP	MP	1	HP	1/SP	HP
c_{14}(YUH)	1/EP	1/MP	1/HP	1	1/EP	1
c_{15}(KWH)	1/LP	1/HP	SP	EP	1	HP
c_{16}(KUH)	1/EP	1/HP	1/HP	1	1/HP	1

Table 9
Evaluation of the sub-criteria of health state index by three experts using linguistic variables.

Three experts	Health state index HS (C_2)		
	c_{21}(PWH)	c_{22}(PWM)	c_{23}(PWL)
c_{21}(WRH)	1	HP	EP
c_{22}(WH)	1/ HP	1	HP
c_{23}(PUH)	1/EP	1/HP	1

Table 10
Evaluation of the sub-criteria of women states index by three experts using linguistic variables.

Three experts	Women state index WC (C_3)		
	c_{31}(WP)	c_{32}(WF)	c_{33}(WO)
c_{31}(WP)	1	MP	EP
c_{32}(WF)	1/MP	1	HP
c_{33}(WO)	1/EP	1/HP	1

Table 11
Evaluation of the sub-criteria of job kind index by three experts using linguistic variables.

Three experts	Job kind index JK (C_4)		
	c_{41}(SHS)	c_{42}(PAS)	c_{43}(WSS)
c_{41}(SHS)	1	MP	EP
c_{42}(PAS)	1/MP	**1**	HP
c_{43}(OS)	1/EP	1/HP	1

Criteria and alternatives discerption

In this section, we identified four main criteria and fifteen sub-criteria which were evaluated based on the age index, health state, women state, and job kind index as illustrated in Fig. 1. The main criteria and sub-criteria were determined based on some reports issued by the World Health Organization and some references that addressed the most important groups. In addition, some experts also suggested these criteria. Due to the importance of some groups, it has been classified in more than one criterion. For example, the age groups were divided into six sub-categories, the elderly, adults, and children, and each of them was divided into sick and healthy people, although they could be included in the sick category.

An overlapping among the main and sub-criteria is shown in Fig. 2. In the main criteria of women, there are three sub-criteria. We assumed that a woman can be a health professional or essential worker which is a sub-criteria of job kind. On the other hand, some women's health status can fall into the sub-criteria of health state and their age can fall into the sub-criteria of Age. Therefore, to some extent, it can be concluded that these criteria can overlap which is depicted in Fig. 2. Table 2 contains a brief description of the main classification evaluation criteria, and then the sub-criteria.

COVID-19 vaccines alternatives

Until now there are more than one hundred COVID-19 vaccine candidates under development according to WHO but only six vaccinations have been approved for limited use according to the New York Times. The best vaccines are determined based on several factors, the most important of which is safety and comprehensive testing before generalization, quality, price, and risks. Given that there is a scarcity of information about COVID-19 vaccines at present for not being tested widely and internationally, it is not possible to know the advantages and disadvantages of COVID-19 vaccines as well as a comparison between them. On the other hand, to find out the most suitable vaccine for the

Table 12
Evaluation of the sub-criteria of age state index by three experts using neutrosophic scale.

Three experts	Age index (C_1)					
	c_{11}(OWH)	c_{12}(OUH)	c_{13}(AWH)	c_{14}(AWH)	c_{15}(KWH)	c_{16}(KUH)
c_{11}(OWH)	1	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	$\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$
c_{12}(OUH)	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	1	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
c_{13}(AWH)	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	1	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	$1/\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
c_{14}(AUH)	$1/\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1	$1/\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	1
c_{15}(KWH)	$1/\langle(0.0,0.1,0.2);0.50,0.10,0.30\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	$\langle(0.2,0.3,0.4);0.80,0.20,0.20\rangle$	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	1	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
c_{16}(KUH)	$1/\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1

Table 13
Evaluation of the sub-criteria of health state index by three experts using neutrosophic scale.

Three experts	Health state index HS (C_2)		
	c_{21}(PWH)	c_{22}(PHR)	c_{23}(PUH)
c_{21}(PHR)	1	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$
c_{22}(PWH)	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
c_{23}(PUH)	$1/\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1

Table 14
Evaluation of the sub-criteria of women state index by three experts using neutrosophic scale.

Three experts	Women state index WC (C_3)		
	c_{31}(WP)	c_{32}(WL)	c_{33}(WO)
c_{31}(WP)	1	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$
c_{32}(WL)	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	1	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
c_{33}(WO)	$1/\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1

Table 15
Evaluation of the sub-criteria of job kind state index by three experts using neutrosophic scale.

Three experts	Job kind index JK (C_4)		
	c_{41}(HP)	c_{42}(EW)	c_{43}(OS)
c_{41}(HP)	1	$\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	$\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$
c_{42}(EW)	$1/\langle(0.4,0.5,0.6);0.90,0.20,0.10\rangle$	**1**	$\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$
c_{43}(OS)	$1/\langle(0.8,0.9,1);0.90,0.10,0.00\rangle$	$1/\langle(0.6,0.7,0.8);0.90,0.10,0.10\rangle$	1

Table 16
De-neutrosophication the sub-criteria of age state index by three experts.

Three experts	Age index (C_1)					
	c_{11}(OWH)	c_{12}(OUH)	c_{13}(AWH)	c_{14}(AUH)	c_{15}(KWH)	c_{16}(KUH)
c_{11}(OWH)	1	4.8750	1.0125	9.4500	1.0125	9.4500
c_{12}(OUH)	0.2051	1	0.2051	4.8750	0.1411	7.0875
c_{13}(AWH)	0.9877	4.8750	1	7.0875	0.3419	7.0875
c_{14}(AUH)	0.1058	0.2051	0.1411	1	0.1058	1
c_{15}(KWH)	0.9877	0.1411	2.9250	9.4500	1	7.0875
c_{16}(KUH)	0.1058	0.1411	0.1411	1	0.1411	1

Table 17
De-neutrosophication the sub-criteria of health state index by three experts.

Three experts	Health state index HS (C_2)		
	c_{21}(PHR)	c_{22}(PWM)	c_{23}(PUH)
c_{21}(PHR)	1	7.0875	9.4500
c_{22}(PWM)	0.1411	1	7.0875
c_{23}(PUH)	0.1058	0.1411	1

Table 18
De-neutrosophication the sub-criteria of women state index by three experts.

Three experts	Women state index WC (C_3)		
	c_{31}(WP)	c_{32}(WL)	c_{33}(WO)
c_{31}(WP)	1	4.8750	9.4500
c_{32}(WL)	0.2051	1	7.0875
c_{33}(WO)	0.1058	0.1411	1

Table 19
De-neutrosophication the sub-criteria of job state index by three experts.

Three experts	Job kind index JK (C_4)		
	c_{41}(HP)	c_{42}(EW)	c_{43}(OS)
c_{41}(HP)	1	4.8750	9.4500
c_{42}(EW)	0.2051	1	7.0875
c_{43}(OS)	0.1058	0.1411	1

different groups is also a challenge. Due to these reasons, we made some assumptions about COVID-19 vaccine alternatives.

The first assumption: we assume that six vaccines have been approved by the World Health Organization and governments and available for allocating in this period.

The second assumption: In this study, we assume that each vaccine of the six available vaccines is more suitable than others for specific groups, for example,

Alternative A1 is more suitable for elderly people.

Alternative A2 would be suitable for people with risk health problems.

Alternative A3 is suitable for pregnant and breastfeeding women.

Alternative A4 would be suitable for health workers and people with more contact with patients and therefore closer to infectious diseases.

Alternative A5 is suitable for healthy people and young people.

Alternative A6 is more suitable for children and young adults.

Proposed approach

In this section, we propose a framework of both AHP and TOPSIS

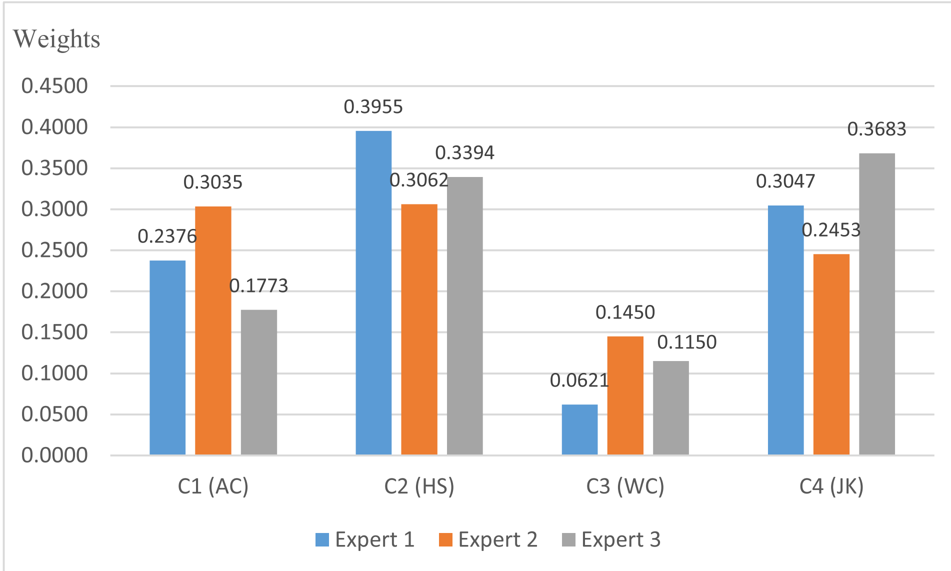

Fig. 3. Ranking of experts for the main criteria.

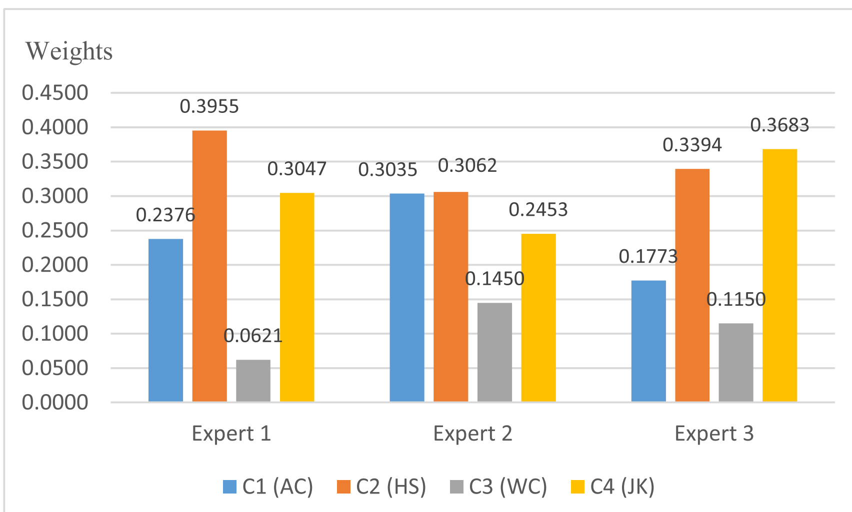

Fig. 4. Ranking of main criteria by three experts.

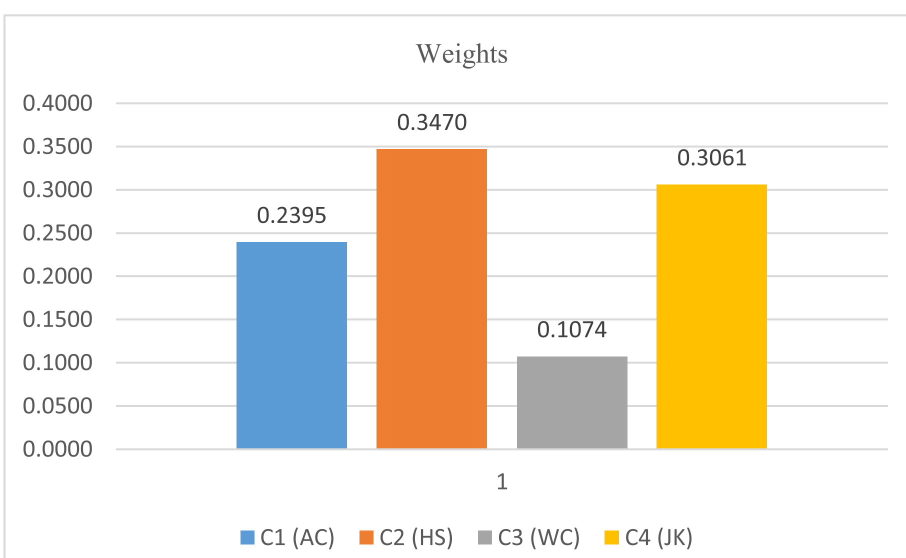

Fig. 5. Final weights of main criteria.

Table 20
Local weights, global weights, and ranking of sub-indices.

Main criteria	**C_1(AC)**						**C_2(HS)**			**C_3(WC)**			**C_4(JK)**		
weight	**0.2395**						**0.3470**			**0.1074**			**0.3061**		
Sub-indices	c_{11}(OWH)	c_{12}(OUH)	c_{13}(AWH)	c_{14}(AUH)	c_{15}(KWH)	c_{16}(KUH)	c_{21}(PHR)	c_{22}(PWH)	c_{23}(PUH)	c_{31}(WP)	c_{32}(WL)	c_{33}(WO)	c_{41}(HP)	c_{42}(EW)	c_{43}(OS)
Local weights	0.3102	0.1006	0.2444	0.0292	0.2853	0.0304	0.7341	0.2129	0.0530	0.7040	0.2423	0.0537	0.7040	0.2423	0.0537
Global weights	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
Local rank	1	4	3	6	2	5	1	2	3	1	2	3	1	2	3
Global rank	4	10	8	14	7	13	1	6	11	3	9	15	2	5	12

Table 21
Evaluation matrix of COVID-19 vaccine alternatives according to sub-criteria.

Expert 1	**c_{11}(OWH)**	**c_{12}(OUH)**	**c_{13}(AWH)**	**c_{14}(AUH)**	**c_{15}(KWH)**	**c_{16}(KUH)**	**c_{21}(PHR)**	**c_{22}(PWH)**	**c_{23}(PUH)**	**c_{31}(WP)**	**c_{32}(WL)**	**c_{33}(WO)**	**c_{41}(HP)**	**c_{42}(EW)**	**c_{43}(OS)**
w	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
A1	EP	EP	SP	SP	LP	LP	SP	SP	SP	SP	SP	SP	SP	SP	SP
A2	HP	LP	HP	LP	HP	LP	HP	MP	LP	SP	SP	SP	SP	SP	SP
A3	LP	LP	LP	LP	LP	LP	LP	LP	LP	EP	EP	SP	LP	LP	LP
A4	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	EP	MP	LP
A5	LP	LP	MP	MP	LP	LP	LP	LP	LP	SP	SP	LP	SP	SP	SP
A6	LP	LP	LP	LP	EP	EP	LP	LP	LP	LP	LP	LP	LP	LP	LP
Expert 2	**c_{11}(OWH)**	**c_{12}(OUH)**	**c_{13}(AWH)**	**c_{14}(AUH)**	**c_{15}(KWH)**	**c_{16}(KUH)**	**c_{21}(PHR)**	**c_{22}(PWH)**	**c_{23}(PUH)**	**c_{31}(WP)**	**c_{32}(WL)**	**c_{33}(WO)**	**c_{41}(HP)**	**c_{42}(EW)**	**c_{43}(OS)**
w	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
A1	HP	HP	SP	SP	LP	LP	SP	SP	SP	SP	SP	SP	SP	SP	SP
A2	MP	LP	MP	LP	MP	LP	MP	SP	LP	SP	SP	SP	SP	SP	SP
A3	LP	LP	LP	LP	LP	LP	LP	LP	LP	HP	HP	SP	SP	SP	SP
A4	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	HP	HP	LP
A5	LP	LP	HP	HP	LP	LP	LP	LP	LP	SP	SP	LP	SP	SP	SP
A6	LP	LP	LP	LP	HP	HP	LP	LP	LP	LP	LP	LP	LP	LP	LP
Expert 3	**c_{11}(OWH)**	**c_{12}(OUH)**	**c_{13}(AWH)**	**c_{14}(AUH)**	**c_{15}(KWH)**	**c_{16}(KUH)**	**c_{21}(PHR)**	**c_{22}(PWH)**	**c_{23}(PUH)**	**c_{31}(WP)**	**c_{32}(WL)**	**c_{33}(WO)**	**c_{41}(HP)**	**c_{42}(EW)**	**c_{43}(OS)**
w	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
A1	MP	MP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP
A2	EP	SP	EP	LP	EP	LP	EP	HP	LP	SP	SP	SP	SP	SP	SP
A3	LP	LP	LP	LP	LP	LP	LP	LP	LP	MP	MP	SP	SP	SP	SP
A4	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	LP	MP	MP	LP
A5	LP	LP	EP	LP	EP	LP	LP	LP	LP	LP	LP	LP	LP	LP	SP
A6	LP	LP	LP	LP	MP	MP	LP	LP	LP	LP	LP	LP	LP	LP	LP

Table 22
De-neutrosophication the evaluation matrix of COVID-19 vaccine alternatives according to sub- criteria.

Expert 1	c_{11}(OWH)	c_{12}(OUH)	c_{13}(AWH)	c_{14}(AUH)	c_{15}(KWH)	c_{16}(KUH)	c_{21}(PHR)	c_{22}(PWH)	c_{23}(PUH)	c_{31}(WP)	c_{32}(WL)	c_{33}(WO)	c_{41}(HP)	c_{42}(EW)	c_{43}(OS)
w	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
A1	9.4500	9.4500	2.9250	2.9250	1.0125	1.0125	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250
A2	7.0875	1.0125	7.0875	1.0125	7.0875	1.0125	7.0875	4.8750	1.0125	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250
A3	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	9.4500	9.4500	2.9250	1.0125	1.0125	1.0125
A4	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	9.4500	4.8750	1.0125
A5	1.0125	1.0125	4.8750	4.8750	1.0125	1.0125	1.0125	1.0125	1.0125	2.9250	2.9250	1.0125	2.9250	2.9250	2.9250
A6	1.0125	1.0125	1.0125	1.0125	9.4500	9.4500	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125
Expert 2	c_{11}(OWH)	c_{12}(OUH)	c_{13}(AWH)	c_{14}(AUH)	c_{15}(KWH)	c_{16}(KUH)	c_{21}(PHR)	c_{22}(PWH)	c_{23}(PUH)	c_{31}(WP)	c_{32}(WL)	c_{33}(WO)	c_{41}(HP)	c_{42}(EW)	c_{43}(OS)
w	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
A1	7.0875	7.0875	2.9250	2.9250	1.0125	1.0125	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250
A2	4.8750	1.0125	4.8750	1.0125	4.8750	1.0125	4.8750	2.9250	1.0125	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250
A3	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	7.0875	7.0875	2.9250	2.9250	2.9250	2.9250
A4	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	7.0875	7.0875	1.0125
A5	1.0125	1.0125	7.0875	7.0875	1.0125	1.0125	1.0125	1.0125	1.0125	2.9250	2.9250	1.0125	2.9250	2.9250	2.9250
A6	1.0125	1.0125	1.0125	1.0125	7.0875	7.0875	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125
Expert 3	c_{11}(OWH)	c_{12}(OUH)	c_{13}(AWH)	c_{14}(AUH)	c_{15}(KWH)	c_{16}(KUH)	c_{21}(PHR)	c_{22}(PWH)	c_{23}(PUH)	c_{31}(WP)	c_{32}(WL)	c_{33}(WO)	c_{41}(HP)	c_{42}(EW)	c_{43}(OS)
w	0.0743	0.0241	0.0585	0.0070	0.0683	0.0073	0.2547	0.0739	0.0184	0.0756	0.0260	0.0058	0.2155	0.0742	0.0164
A1	4.8750	4.8750	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125
A2	9.4500	2.9250	9.4500	1.0125	9.4500	1.0125	9.4500	7.0875	1.0125	2.9250	2.9250	2.9250	2.9250	2.9250	2.9250
A3	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	4.8750	4.8750	2.9250	2.9250	2.9250	2.9250
A4	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	4.8750	4.8750	1.0125
A5	1.0125	1.0125	9.4500	1.0125	9.4500	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	2.9250
A6	1.0125	1.0125	1.0125	1.0125	4.8750	4.8750	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125	1.0125

methods. Here, we assume three experts will give the weights of each group and COVID-19 vaccine alternatives. Moreover, the weights are considered as neutrosophic numbers.

The main phases of the proposed approach are as follows:

Phase 1: the experts' phase
Collect the essential date.
Identify the main criteria, sub-criteria, and COVID-19 vaccines alternatives.
Evaluate the main criteria, sub-criteria, and COVID-19 vaccines alternatives.
Confirm the evaluation of the main criteria, sub-criteria, and alternatives.
Construct the hierarchy structure
Phase 2: Criteria evaluation (Neutrosophic-AHP)
Experts' construct a pairwise comparison.
Deneutrosophication the neutrosophic numbers to real value using Eq. (15), then take the average.
Normalize the evaluation matrix.
Check comparison consistency using Eq. (1).
Find the weights.
Phase 3: Ranking alternatives (Neutrosophic-TOPSIS)
Construct an evaluation matrix between the sub-criteria and alternatives by three experts.
Deneutrosophication the neutrosophic numbers to real value using Eq. (15), then take the average.
Normalize the evaluation matrix.
Determine the positive ideal solution and the negative ideal solution (PIS, NIS) using Eqs. (4) and (5).
Rank alternatives according to the relative coefficient using Eq. (8).
Keep the superlative alternative
Phase 4: Recommendations
Recommend the priority of groups and the superior alternative.

Results and discussions

Three experts' opinion is considered in this proposed model. The below-mentioned tables depicting the linguistic variables, rating of alternatives, evaluation of main and sub-criteria, and also the rating of neutrosophic for main and sub-criteria.

Table 3 presents linguistic variables used for weighting the main criteria and sub-criteria which are identified based on the Eqs. (11), (12), and (13).

Table 4, Table 8, Table 9, Table 10, Table 11, and Table 21, report the evaluation of main criteria, sub-criteria, and rating of alternatives by three experts using linguistic variables. While Table 5, Table 12, Table 13, Table 14, and Table 15 presents neutrosophic ratings of main criteria, sub-criteria, and alternatives. The de-neutrosophiction is shown in Table 6, Table 16, Table 17, Table 18, and Table 19.

It clears from Table 7 that the health state index is the most important main criteria with weight 0.3470 followed by the job kind index with weight 0.3061. Then the age index with weight 0.2395 and finally the state of women with weight 0.1074. Fig. 3 and Fig. 4 show the ranks of the main criteria by the three experts while Fig. 5 illustrates the final weights of the main criteria.

Table 20 shows the local and global weights with the sub-criteria ranking. The ranks of sub-criteria of the age index are the priority for the people with health problems for all aged people like the elderly, kids, and adults respectively and then the healthy elderly, kids, and adults respectively. The ranks of sub-criteria of the health states index are the people with high-risk health problems rank first then the people with moderate health problems while the healthy people come in the last rank with weights 0.0184.

About the sub-indicators of the women's state criterion, pregnant rank first with a weight of 0.0756 while the lactated mothers rank second with a weight of 0.0260. The women who are not pregnant or breastfeeding come lastly with a weight of 0.0058.

Moreover, the ranks of the sub-criteria of the job kind are as follows: the workers in the health sector rank first with a weight of 0.2155 while the essential workers get the second rank with a weight of 0.0742. Then, the workers in the other sectors come in the last rank with a weight of 0.0164.

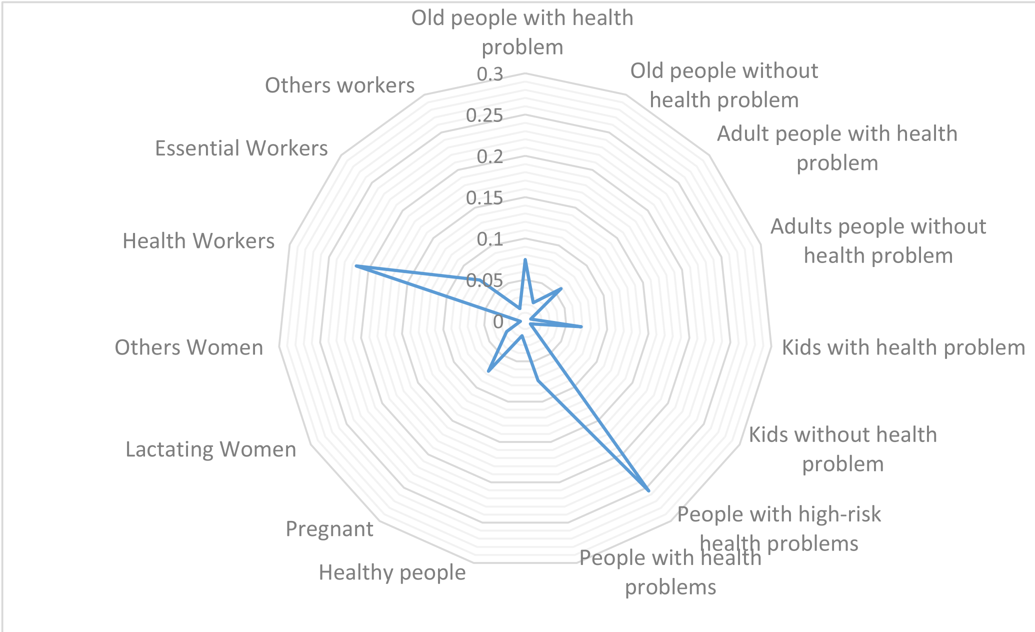

Fig. 6. Final weights of sub-criteria.

Table 23
Ranking of alternatives by TOPSIS method.

Alternatives	$dS^+{}_i$	$dS^-{}_i$	Performance score p_i	Rank (PS_i)
A_1	0.2149	0.0759	0.2610	3
A_2	0.1162	0.2245	0.6589	1
A_3	0.2517	0.0671	0.2105	4
A_4	0.2265	0.1578	0.4106	2
A_5	0.2515	0.0531	0.1743	5
A_6	0.2734	0.0387	0.1240	6

On the final rank level, the people with high-risk health problem rank first with a weight of 0.2547 followed by the health workers with a weight of 0.2155, pregnant, patient's elderly, essential workers, people with a normal health problem, kids and adults with normal health problems, lactated mothers, healthy elderly, healthy people, workers in the other sectors, in the last ranks, the healthy people whatever adult or kids as shown in Fig. 6.

Thus, individuals with high-risk health problems have the extreme priority to take doses of the COVID-19 vaccine first, regardless of their age, gender, or occupation. When differentiating between patients, the priority will be first for elderly patients, then for children patients, then for adult patients. Also, Pregnant women get priority over breastfeeding mothers and the health workers over the essential workers. For healthy people, the elderly come first, then children and adults at last.

Table 23 illustrates the Euclidean distance between the positive perfect solution ds_i^+ and negative perfect solution ds_i^- which is calculated using Eqs. (6, 7). Also, it shows the PS_i calculated via (8). Moreover, as it is clear in Table 22, the appropriate COVID-19 vaccine for patients get the highest priority, while the most appropriate COVID-19 vaccine for the medical personnel comes second in terms of priority.

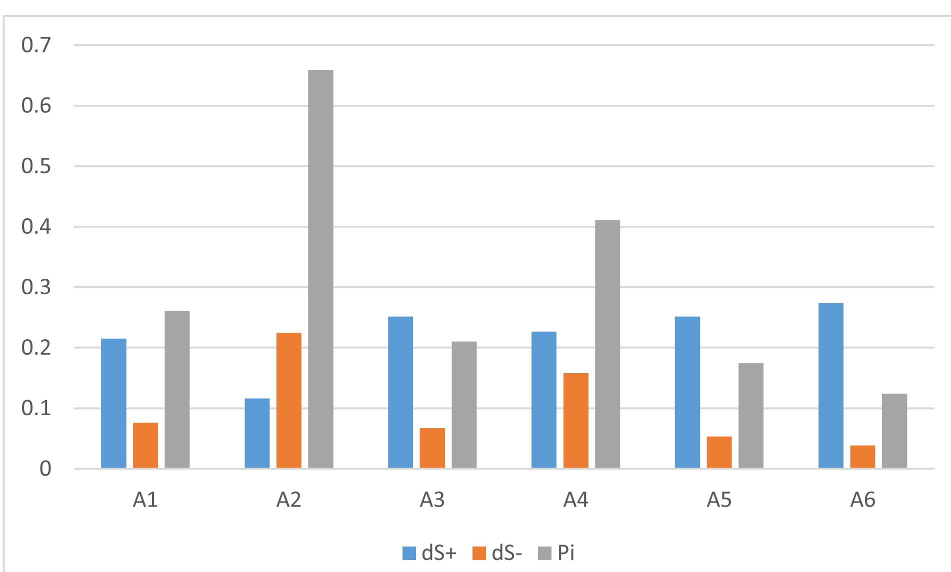

Fig. 7. Final ranking of COVID-19 vaccine alternatives by TOPSIS method.

After that, the COVID-19 vaccines which are more suitable for the elderly and pregnant/lactating women, and lastly, the suitable vaccines for children and youth. Fig. 7 also shows the final rank of the COVID-19 vaccine alternatives.

Overall, this work defined the selection criteria to rank the most eligible groups to receive the COVID-19 vaccine first. Since the number of COVID-19 infected patients is increasing day by day, it is a great concern for all groups of society not being able to vaccinate. Therefore, a scheduling plan must be made so that the first payment of COVID-19 vaccines for the most vulnerable groups who if infected with the virus.

Moreover, the COVID-19 vaccine alternatives were ranked using the TOPSIS method. Due to the lack of information about these alternatives, it has been assumed that each vaccine is more useful for a specific group better than others and has been ranked on these rules.

The lofty goals of governments are reducing deaths, straighten the curb of COVID-19 infected patients, and well-being for all humans. So, the present approach gives governments an outline for scheduling society groups according to need by optimizing the allocation process as well as selecting the most appropriate vaccine. Also, the proposed approach was more flexible because the inputs were neutrosophic, and more than one expert opinion was adopted. Other categories and experts could be added if there arises any necessity. Therefore, this study can be considered comprehensive in this area and can be applied in similar applications such as treatment priority and others.

Conclusion

The world is racing against time to find vaccines for COVID-19. Only a few may complete all phases of trial and get approval, but the available doses will not cover the needs of all populations in this period. And because of the limited doses of vaccines, some fear a lack of fair allocation at both the global level between countries and the local level among the different groups of society. Therefore, it was necessary to establish guidelines and a timetable for allocating the primarily available COVID-19 vaccines until vaccines are available in abundance to all. This study aims to develop a preliminary vision for classifying and ranking the most deserving groups in the society so that they have priority in taking the vaccine first. AHP method under uncertainty was used to evaluate and rank the main and sub-criteria, as the inputs were neutrophilic numbers, which gave greater flexibility to the study. Then, neutrosophic TOPSIS was also applied to rank the COVID-19 vaccine alternatives. The results obtained from the work indicated the importance of classification and ranking, as priority was given to critically ill individuals, health workers, elderly, pregnant, and lactating women. Based on the weights of the sub-criteria, the appropriate COVID-19 vaccine was chosen as the best alternative. Future studies can be done by including more groups as well as more experts. Furthermore, the COVID-19 vaccine can be classified according to cost, safety, availability, and delivery.

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CRediT authorship contribution statement

Ibrahim M. Hezam: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Moddassir Khan Nayeem:** Data curation, Writing - review & editing. **Abdelaziz Foul:** Revision of draft preparation. **Adel Fahad Alrasheedi:** Revision of draft preparation. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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