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# Primus inter pares: A Comparison and Ranking of COVID-19 Vaccines

Eyüp Çetin[1*], Hilal Özen[2] and Ömer Özen[3]

*[1]New York Business Global, Silver Spring, Maryland, USA*
*[2]Department of Business Administration, Faculty of Economics and Administrative Sciences, Trakya University, Edirne, Turkey*
*[3]Department of Informatics, Istanbul University, Istanbul, Turkey*

**Abstract.**

As the world fights the recent devastating calamity, coronavirus pandemic, humanity experiences the most accelerated vaccine development and vaccination in history. We holistically compare, rate and rank SARS-Cov-2 vaccines as well as vaccine platforms in multi-attributes as the first study in the literature. We use grey relational analysis as a multi-criteria decision-making tool, wider grey systems theory to compare, rate and rank the vaccines. We select 12 leading vaccines and 14 attributes from efficacy rate, safety/reactogenicity and protection against variants to children use, from approvals to prices, to logistics and market share to form a 360-degree comparison. According to equally weighted attributes, Pfizer/BioNTech vaccine is at the top rank. The second rank belongs to Moderna when the third belongs to Sinovac. The top three are followed by Oxford-AstraZeneca, Johnson & Johnson, and others. Pfizer/BioNTech is also at the first rank and followed by Moderna and Novavax with respect to 40% weighted efficacy rate. Our ranking approach, which is unbiased and reproducible employs a Wuhan-originated tool, grey systems theory to rank the vaccines against SARS-CoV-2, another Wuhan-originated agent. Since all vaccines are valuable, our effort is to determine the primus inter pares (= first among equals)

**JEL Classification:** I1, I18, C00, C02.

**Keywords and Phrases:** COVID-19 vaccines, Vaccination, SARS-CoV-2, Vaccine comparison and ranking, Health policy, Grey relational analysis.

* Corresponding author
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*E-mail addresses*: eyup.cetin@ejpam.com (EC), hilalozen@trakya.edu.tr (HO), omer.ozen@ogr.iu.edu.tr (OO)

*While the vaccine discovery was progressive, the joy I felt at the prospect before me of being the instrument destined to take away from the world one of its greatest calamities…* (Baron, 1827)

– Edward Jenner (1749-1823), "The Father of Vaccination"

## 1. Introduction

The world has been fighting the recent devastating calamity called coronavirus pandemic (COVID-19) with a death toll of almost 4 million out of almost 185 million confirmed cases (World Health Organization-WHO, 2021). There are several well-known weapons to combat COVID-19 such as face masks, social distancing, lockdowns, and vaccines (see Cetin, Kiremitci, and Kiremitci (2020) for a weapon-target analogy and optimal policies to fight pandemics and COVID-19).

The most effective weapon to fight the invisible enemy and achieve global immunity is vaccines. Considering the seriousness of the situation that Louis Pasteur (1822–1895), as many honors him as the first immunologist, (Morgan and Parker, 2007) quotes "Gentlemen, it is the microbes who will have the last word" [Messieurs, c'est les microbes qui auront le dernier mot], many researchers and institutions have fortunately started a vaccine development race against SARS-CoV-2, which is the most accelerated vaccine progress in the history of vaccination goes back to 1000 AD (Flemming, 2020). As a result of this ongoing heavy efforts, we believe humanity shares the joy of Edward Jenner (1749-1823), who is regarded as the Father of Immunology or Vaccination, (Flemming, 2020) in the opening quotation in this study because the 95 vaccines are currently tested in clinical trials on humans, and 32 have reached the final stages of testing. Researchers investigate at least 77 preclinical vaccines in animals. Also, 9 vaccines have been authorized for early use when 8 vaccines have been approved for full use (Zimmer, Corum and Lee, 2021).

In addition to the fast ever vaccine development, the vaccination is also the biggest vaccine campaign in the history as more than 4.62 billion doses administrated so far in the world with a current rate of 37.9 million shots a day on 13 August 2021 (Bloomberg, 2021). This is indeed a record-breaking mobilization.

In this study, we compare rate and rank COVID-19 vaccines as well as vaccine platforms using grey systems theory, particularly grey relational analysis. This is the first study in the literature to rank SARS-CoV-2 vaccines in many dimensions and as well as employ grey systems theory for the comparison. We consider non-randomly selected 12 vaccines listed as leading vaccines, for which the published and reliable data is available according to the comparison attributes that we consider, in The New York Times Coronavirus Vaccine Tracker (Zimmer, Corum and Wee, 2021).

We select efficacy rate, the number of doses, duration between doses, safety and reactogenicity, protection against variants, children use ability, and storage conditions as comparison attributes. In addition to clinical performance, the approval and accreditation attributes are also included such as fully approval, emergency use approval and World Health Organization's emergency use approval as well as the stopping of use as an implicit extreme side effect indication. To form a 360-degree comparison, for the accessibility measures, the attributes of price, logistics, and market share are also successfully included to feed the model of grey relational analysis, wider grey systems theory. The phase status of a

vaccine is not included since all vaccines in the sample are in the Phase 3, and hence it is not distinguishing attribute for comparison. These 14 attributes are defined and explained in detail in the related sections below.

## 2. Related Literature

There is growing subset literature on SARS-Cov-2 or COVID-19 vaccines in the huge literature of vaccines. In the base of comparison of COVID-19 vaccines, the literature is extremely scarce and most of the studies in this valley are comparison of mainly pair of vaccines or a comparison of more vaccines in one dimension. For instances, Rogliani et. al., (2021) compares the efficacy of candidate vaccines in inducing neutralizing antibodies against SARS-CoV-2. Meo et.al (2021), compares the pharmacology, indications, contraindications, and adverse effects of the Pfizer/BioNTech and Moderna vaccines when Rapaka et. al. (2020) discusses critical variables to consider for comparing efficacy measurements across current and future COVID-19 vaccine trials. Also, Peiffer-Smadja et. al. (2021) presents some comparative facts including variants for main vaccines in use. Besides, Funk, Laferrière, and Ardakani (2021) compares SARS-CoV-2 vaccine platforms.

Regarding grey relational analysis as a multi-criteria decision-making tool and grey systems theory, there is a huge literature with applications to business, economics, engineering, earth sciences, and social sciences, but relatively rare in health sciences, health care management and medicine. Some applications and comprehensive information of grey relational analysis and grey systems theory can be found in Liu, Yang and Forrest (2017) and Yin (2013).

There is no study providing holistic head-to-head comparison, rating, and ranking for SARS-CoV-2 vaccines, even in multi-attributes, and even using grey systems theory in the literature. This is the first study for grey systems theoretic holistic comparison, rating and ranking of COVID-19 vaccines and vaccine platforms in multi-attributes to determine the primus inter pares (= first among equals). The paper is organized as follows; Materials and Methods, Results and Discussion, and Conclusions.

## 3. Methods

### *3.1.Grey Systems Theory*

Grey systems theory was established by Ju Long Deng at Huazhong University of Science and Technology, China in 1982 by his two seminal papers Deng, J. L., (1982a) and Deng, J. L., (1982b). It focuses on the study of problems involving small samples and poor information. In an analogy for the use of colors to describe the degree of clearness of available information, systems with completely known information are regarded as white, when systems with completely unknown information are considered black, and systems with partially known information and partially unknown information are seen as grey (Liu, Yang, and Forrest, 2017).

The grey systems theory deals with uncertain systems that contain partially known information through generating, excavating, and extracting useful information from the available information. Many uncertain systems with small samples and poor information commonly exist in the real-world grey (Liu, Yang, and Forrest, 2017). This fact determines the wide applicability of grey systems theory from economics and earth sciences to environment and engineering, to business and social sciences, but relatively rare in

medicine, health sciences and health care management. The grey systems theory, emerged from Wuhan, China, has become a phenomenon like a-very-useful-pandemic across the world and disciplines.

*3.2.Grey Numbers and Whitenization*

A grey system is characterized by grey numbers, grey sequences, grey equations, or matrices. In applications, a grey number signifies an indeterminate number that takes its possible value within an interval or a general set of numbers. A grey number that represents the degree of information uncertainty in a given system is generally denoted using the symbol "⊗", which is called grey.

There are several types of grey numbers such as grey numbers with only a lower bound, grey numbers with only an upper bound, continuous and discrete grey numbers, interval grey numbers, and black and white numbers. Interval grey number ⊗ has both a lower bound $\underline{a}$ and an upper bound $\overline{a}$, and denoted $\otimes \in [\underline{a}, \overline{a}]$. Black numbers are represented as $\otimes \in (-\infty, +\infty)$; that is when ⊗ has neither an upper nor a lower bound, then ⊗ is known as a black number. When $\otimes \in [\underline{a}, \overline{a}]$ and $\underline{a} = \overline{a}$, ⊗ is known as a white number (Liu, Yang, and Forrest, 2017).

The definite white number is referred to as the whitenization (value) of the grey number, denoted $\widetilde{\otimes}$. For the general interval grey number $\otimes \in [a, b]$, its whitenization value $\widetilde{\otimes}$ can be taken, based on the possible value information, given as; $\widetilde{\otimes} = \alpha a + (1-\alpha)b, \alpha \in [0,1]$ where $\alpha$ is called the positioned coefficient of the interval grey number $\otimes \in [a, b]$. By definition, mean whitenization occurs when $\alpha = {}^{1}/_{2}$. As the distribution of an interval grey number is unknown, mean whitenization is frequently used (Liu, Yang, and Forrest, 2017).

*3.3.Grey Relational Analysis*

Grey relational analysis (GRA) which is also known as grey incidence analysis (GIA) is the most widely used component of grey systems theory. It is also recognized as a tool of multi-attribute decision making. Unlike traditional methods of statistics which generally require larger sample sizes and underlying probability distributions, the GRA (or GIA) works well even for the systems with small samples, no probability distributions and poor information where statistical methods do not seem appropriate.

In addition, the amount of computation involved is small and can be carried out conveniently, without issues of disagreement between quantitative and qualitative conclusions (Liu, Yang, and Forrest, 2017).

The implementation steps of grey relational analysis are as follows; determination of grey relational generating (normalization of the data), defining reference sequence, calculating grey relational coefficient, and finally obtaining grey relational grade for comparison and ranking.

The steps for the implementation of GRA are given in detail as follows (Kuo, Yang, Huang, 2008).

### *3.3.1. Grey relational generating*

In order to compare different attributes (or criteria) with different ranges in different units, we need to transform the data into a comparable standard plane, that is, a normalization of the data into $[0,1]$ for each attribute along with each alternative.

Assuming there are $m$ alternatives and $n$ attributes, the $i$th alternative can be denoted as $Y_i = (y_{1i}, y_{2i}, y_{3i,} \dots, y_{ij}, \dots, y_{in})$, where $y_{ij}$ is the performance value of attribute $j$ for alternative $i$. The vector $Y_i$ can be converted into the comparability sequence $X_i = (x_{i1}, x_{i2}, x_{3i,} \dots, x_{ij}, \dots, x_{in})$ by use of one of the appropriate equations with respect to the nature of the attributes.

For "the larger, the-better" attributes,

$$x_{ij} = \frac{y_{ij} - min\{y_{ij}, i = 1,2, \dots, m\}}{max\{y_{ij}, i = 1,2, \dots, m\} - min\{y_{ij}, i = 1,2, \dots, m\}} \quad for\ i = 1,2, \dots, m, \qquad j = 1,2, \dots, n.$$

(Eq. 1)

For "the smaller, the better" attributes,

$$x_{ij} = \frac{max\{y_{ij}, i = 1,2, \dots, m\} - y_{ij}}{max\{y_{ij}, i = 1,2, \dots, m\} - min\{y_{ij}, i = 1,2, \dots, m\}} \quad for\ i = 1,2, \dots, m, \qquad j = 1,2, \dots, n.$$

(Eq. 2)

For "the closer to the desired value $y_j^*$, the better" attributes,

$$x_{ij} = 1 - \frac{|y_{ij} - y_j^*|}{max\left\{max\{y_{ij}, i = 1,2, \dots, m\} - y_{ij}^*, y_{ij}^* - min\{y_{ij}, i = 1,2, \dots, m\}\right\}} \quad for\ i = 1,2, \dots, m, j = 1,2, \dots, n.$$

(Eq. 3)

### *3.3.2. Defining reference sequence*

As a consequence of grey relational generating step, all data is normalized into a standard scale $[0,1]$. An alternative $i$ will be the best choice for attribute $j$ if all its performance values are closest to or equal to 1. However, such kind of ideal alternative does not usually exist. In this work, we define the reference sequence (or vector) $X_0 = (x_{01}, x_{02}, x_{03,} \dots, x_{0j}, \dots, x_{0n}) = (1,1,1 \dots, 1, \dots, 1)$, and goal to find the alternative $i$ whose comparability sequence is the closest to the reference sequence.

### *3.3.3. Calculating grey relational coefficient*

Grey relational coefficient is a measure for the closeness $x_{ij}$to $x_{0j}$. The larger grey relational coefficient means $x_{ij}$ are $x_{0j}$ are closer. The grey relational coefficient between $x_{ij}$ and $x_{0j}$ is denoted by $\gamma(x_{0j}, x_{ij})$ and can be obtained by the equation;

$$\gamma(x_{0j}, x_{ij}) = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{ij} + \zeta\Delta_{max}} \quad for\ i = 1,2,\dots,m, \qquad j = 1,2,\dots,n,$$

(Eq. 4)

where $\Delta_{ij} = |x_{0j} - x_{ij}|$,

$\Delta_{min} = min\{\Delta_{ij}, i = 1,2,\dots,m;\ j = 1,2,\dots,n\}$,

$\Delta_{max} = max\{\Delta_{ij}, i = 1,2,\dots,m;\ j = 1,2,\dots,n\}$, and

$\zeta \in [0,1]$ is the distinguishing coefficient.

The distinguishing coefficient is used to expand or compress the range of the grey relational coefficient. It can be selected by the decision maker and any arbitrary selection would change the value of grey relational coefficients; however, its selection does not change the rank order of the grey relational coefficients, on which we focus. In this effort, we consider the distinguishing coefficient $\zeta = 0.5$ as common selection in the literature.

### *3.3.4. Obtaining gray relational grade*

Once all grey relational coefficients $\gamma(x_{0j}, x_{ij})$ are calculated, the grey relational grade can be obtained by the following equation; the grey relational grade between $X_0$ and $X_i$ is,

$$\Gamma(X_0, X_i) = \sum_{j=1}^{n} w_j\, \gamma(x_{0j}, x_{ij}) \quad for\ i = 1,2,\dots,m,$$

(Eq. 5)

where $w_j$ is the weight of attribute $j$ and $\sum_{j=1}^{n} w_j = 1$. It depends on the decision maker and relative importance of the attributes to each other, i.e. the nature of the system. This weighting effort is a common procedure in most of multi-attribute and multi-criteria decision making models. If all attributes are equally important or nonpreemptive, then the weights can be equally selected as $w_j = {}^{1}/_{n}$.

The grey relational grade shows the degree of similarity between the comparability sequence and the reference sequence. If a comparability sequence for an alternative gets the highest grey relational grade with the reference sequence, it means that the comparability sequence is most similar to the reference sequence, and that alternative would be the best choice.

### *3.4.Rating and Ranking of SARS-CoV-2 Vaccines Using Grey Relational Analysis*

In this study, we propose the use of grey relational analysis, wider grey systems theory, to obtain a comparison, rating, and ranking frame of SARS-CoV-2 vaccines in appropriate attributes. The approach can be employed with finite number of vaccines ($m$) and attributes ($n$). This frame can be used for any kind of clinical agents in any subject category and related attributes (or performance criteria).

We compare, rate and rank the leading SARS-CoV-2 vaccines listed in The New York Times Coronavirus Vaccine Tracker (The NYT Coronavirus Vaccine Tracker), the number of the leading vaccines is 12, the sample size of our non-random sample.

#### *3.4.1. Data Source*

We select and define appropriate 14 attributes (or performance criteria) that are distinguishing and making sense to form a comparison, rating and ranking frame as follows - the data is mainly taken from The New York Times Coronavirus Vaccine Tracker (Zimmer, Corum and Lee, 2021) and others cited respectively for the selected vaccines and attributes, and presented in Table 1 and Table 2;

*Approved*: Initial authorization of a vaccine in at least one country. If a vaccine has been approved for delivery in at least one country, we quantify 1, otherwise 0. It is clearly type of "the larger, the-better" attribute. There has been no vaccine with full approvement to the date, August 13, 2021.

*Emergency Use*: Approvement for emergency use in at least one country such as in US, EU or any other country. If a vaccine is adopted and approved for emergency use in at least one country, it is valued as 1, if not 0. It is also clearly type of "the larger, the-better" attribute.

*WHO's Emergency Use Approval*: Approvement for emergency use by the World Health Organization (WHO). If a vaccine is approved for emergency use by WHO, we value as 1, otherwise 0. This is also a sort of "the larger, the-better" attribute like the Emergency Use attribute, from which but different and distinguishing criterion.

*Efficacy Rate*: Efficacy rate of a vaccine against SARS-CoV-2. This is one of the most important and distinguishing attributes and naturally "the larger, the-better" performance criterion. The efficacy rates of the selected vaccines Pfizer-BioNTech, Moderna, Gamaleya, Oxford-AstraZeneca, CanSino, Johnson & Johnson, Novavax, Sinopharm, Sinovac, Sinopharm-Wuhan, Bharat Biotech, and Vector Institute are tabulated in Table 1 (Zimmer, Corum and Lee, 2021). The efficacy rate of the vaccine Vector Institute is currently unknown; thus, we consider the median of the efficacy rates of other 11 vaccines as its substitute efficacy rate, which is 0.78.

*Dose*: The number doses of a vaccine to be fully delivered. As the fast achievement of herd immunity is desired, this attribute is considered as a type of "the smaller, the better" attribute. Since the dose

information of the vaccine Sinopharm-Wuhan is not available, we take the median of that of other 11 vaccines, which yields 2 doses.

*Weeks:* The number of weeks between doses of a vaccine to be fully delivered. Like the attribute Dose, the attribute Weeks is also a sort of "the smaller, the better" attribute to achieve a rapid herd immunity. Taking the only attributes Dose and Weeks into account, the ideal profile could be one-shot vaccine regime such as Johnson & Johnson. The number of Weeks becomes 0 for one-shot vaccines. The Weeks value for vaccine Sinopharm-Wuhan is not available, we again substitute the median of other vaccines' Weeks value giving 3 weeks.

*Storage*: Storage and distribution temperature (in °C) of a vaccine. The vaccines should be stored in different mediums such as ultra-cold freezer, freezer, thermal shipping container, refrigerator, and room temperature. We consider the storage temperatures which is required for the long run storage until their expiration dates.

As the storage data is given as intervals; for instance, Pfizer-BioNTech should be stored in an ultra-cold freezer between -80ºC and -60ºC (CDC, 2021a), hence, by mean whitenization in grey systems theory, that is, $\otimes \in [-80,-60]$, $\widetilde{\otimes} = \alpha a + (1-\alpha)b, \alpha \in [0,1] = 0.5(-80) + 0.5(-60) = -70,$ then we get the storage temperature of Pfizer-BioNTech as -70 ºC. Similarly, Moderna vaccine should be kept in a freezer between -50°C and -15°C (CDC, 2021b), by mean whitenization, we obtain $\widetilde{\otimes} = 0.5(-50) + 0.5(-15) = -32.5$. The storage values of other vaccines are taken from The NYT Coronavirus Vaccine Tracker (Zimmer, Corum and Lee, 2021) and their mean whitenization are calculated as shown in Table 2. Since the storage data for the Sinopharm and Sinopharm-Wuhan vaccines are not available, we substitute their values with the median storage values of other 10 vaccines which results in 5°C. The storage information for Bharat Biotech vaccine is only available as "at least a week at room temperature" in The NYT Coronavirus Vaccine Tracker (Zimmer, Corum and Lee, 2021), thus, we take its value 22.5 °C as the mean whitenization of room temperature 20°C and 25°C (Louisiana Department of Health, 2021). The Gamaleya vaccine can be stored in a refrigerator between 2ºC and 8ºC (sputnikvaccine.com, 2021).

In this study, we consider the refrigerator between 2ºC and 8ºC as an ideal storage medium due to its common feasibility and less cost. The mean whitenization of 2ºC and 8ºC is 5ºC which serves as the desired value $y_j^*$ for "the closer to the desired value $y_j^*$, the better" attribute Storage.

*Price*: The price per dose of a vaccine in USD. This is an important attribute as an accessibility measure to the vaccines especially in vaccine shortage. The prices of the vaccines vary from country to country across the world. We calculate the median vaccine prices of the countries bought vaccines for each vaccine from the UNICEF data, (UNICEF, 2021). and present in Table 1. The price of Sinopharm-Wuhan vaccine is not available, we assume and take the price of another Sinopharm vaccine $ 29.75 as a substitute price since the co-developer is Sinopharm with the assumption of adoption of the same price policy. The price for CanSino vaccine is also not available, then we take the median vaccine prices of other 11 vaccines for the missing value. This is clearly a kind of "the smaller, the better" attribute.

*Logistics*: The Logistics Performance Indexes of vaccine developer countries. Logistics, a component of supply chain management, is another important performance measure for vaccines, yet it is too difficult

to obtain a comparative supply chain and logistics performance values of developers and manufacturers. As the world has experienced that the governments constrained the logistics and supply chains of developer companies by regulations, particularly in their early production, thus, as a representative variable for vaccine logistics, we consider the Logistics Performance Indexes (LPI) of developer countries. That is also reasonable due to that the companies use the logistics channels and efforts of their countries with the assumption that huge amounts of vaccines are manufactured in the developer countries. We employ The World Bank Global Logistics Performance Index 2018, the most recent ranking (The World Bank, 2018). This attribute is of "the larger, the-better".

If there are multiple developers for a vaccine, we evaluate the mean of LPIs of the countries as the related vaccine logistics performance. For instance, Pfizer-BioNTech is developed by Pfizer of the US and BioNTech of Germany, the logistics performance score for Pfizer-BioNTech vaccine is the mean of 3.89 of the US (#14 in the world) and 4.20 of Germany (#1 in the world) is 4.045. All logistics scores for vaccines are shown in Table 1.

*Safety/Reactogenicity*: A given score for the comparison of SARS-CoV-2 vaccine platforms in the safety/reactogenicity dimension, published in (Funk, Laferrière, and Ardakani, 2021); in this study, the authors value the mRNA and the protein platforms 24, the viral vector platform 21, and the inactivated virus platform 30, out of 30. Thus, as a performance of safety/reactogenicity which is "the larger, the-better" attribute, we give those scores to the related SARS-CoV-2 vaccines on the related vaccine platforms, respectively, presented in Table 1.

*Variants*: The protection against at least one coronavirus variant. The Alpha, Beta, Gamma and Delta variants are main variants of concern, especially the highly transmissible Delta variant seems to appear at alarming level all over the world. The protection against variants is another vital performance measure that is considered as "the larger, the-better" attribute, in this study, since if a vaccine protects against at least one variant, given 1, otherwise 0, see Variants Column in the Table 1 and Table 2 (Stieg, 2021; Emary et al., 2021).

*Market Share*: The global market share of a vaccine. This is another substantial attribute of vaccines as the indications of reputation, and supply and demand efforts. We calculate the market shares of the vaccines from the UNICEF data by considering all Formalized doses under Agreement Status for all countries (UNICEF, 2021). According to our calculations, Pfizer/BioNTech vaccine is a market leader with a share of 27.52%, followed by Oxford-AstraZeneca with 17.06% and Novovax 10.82%. Our span, the leading vaccines, holds the 86.64% of the global SARS-CoV-2 vaccine market, given in detail Table 1. The Market Share is also a sort of "the larger, the-better" attribute.

*Children*: Approvement of a vaccine for the use of children as young as 12 in at least one country. This is also a distinguishing attribute for the comparison and rating of the vaccines, due to that the authorization of children use extends the vaccinated population to achieve herd immunity faster. Then, this is also a "the larger, the-better" attribute. We give 1 if a vaccine has authorization for children use such as Pfizer/BioNTech, and Moderna (Zimmer, Corum, and Wee, 2021). Some vaccines developers are running trials for children between the ages of 5 and 11, yet they are not finished (Zimmer, Corum, and Wee, 2021).

*Stopped*: Stopping the use of a vaccine in at least one country. The stopped use of a vaccine due to a specific side effect such as severe cases of blood clots is a certain disadvantage for the vaccine, even they are very rare cases. The Johnson & Johnson vaccine has been stopped in Denmark and Finland, and Oxford-AstraZeneca vaccine has been stopped in Denmark and Norway (Zimmer, Corum, and Wee, 2021). We quantify 1 if a vaccine has been stopped in at least one country, otherwise 0. This attribute which may implicitly represent extreme side effects is a "the smaller, the better" criterion.

We consider and select 14 attributes to compare, rate and rank the chosen 12 leading SARS-CoV-2 vaccines, the size of $mxn = 12x14$, their qualitative and quantitative data are presented in Table 1. Other relevant attributes might also be included such as the phase status and side effects of the vaccines. All vaccines in our sample, the leading vaccines, have been reached the Phase 3, so this attribute is not a distinguishing criterion, then we do not include the phase status. Regarding side effects, we do not see published comparable data for the same side effect cases for all vaccines. However, the Stopped attribute may also serve implicitly as a substitute severe side effect indicator.

We handle all interval data using mean whitenization and categorical data as well as missing values to obtain single numerical values as explained in detail in the definition of attributes above, respectively, and present the quantified data of the vaccines with respect to the related attributes in Table 2.

**Table 1. The raw data for the vaccines by attributes**

| Developer | Country | Vaccine Name | How It Works | Approved | Emergency Use | Emergency Use by WHO | Efficacy Rate (%) | Dose | Weeks | Storage | Price (USD) | Logistics | Safety/ Reactogenicity | Variants | Market Share (%) | Children | Stopped Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pfizer-BioNTech | US-Germany | Comirnaty | mRNA | Yes | Yes | Yes | 91.30 | 2 | 3 | -80ºC to -60ºC | 19.50 | 4.045 | 24 | Yes | 27.525 | Yes | No |
| Moderna | US | mRNA-1273 | mRNA | Yes | Yes | Yes | 92.50 | 2 | 4 | -50°C to -15°C | 15.00 | 3.890 | 24 | Yes | 10.040 | Yes | No |
| Gamaleya | Russia | Sputnik V | Ad26. Ad5 | No | Yes | No | 91.60 | 2 | 3 | 2ºC to 8ºC | 16.29 | 2.760 | 21 | No | 4.625 | No | No |
| Oxford-AstraZeneca | UK-Sweden | Vaxzevria | ChAdOx1 | Yes | Yes | Yes | 76 | 2 | 4 | Refrigerator | 4.00 | 4.020 | 21 | Yes | 17.068 | No | Yes |
| CanSino | China | Convidecia | Ad5 | Yes | Yes | No | 65.28 | 1 | 0 | Refrigerator | N/A | 3.610 | 21 | No | 0.401 | No | No |
| Johnson & Johnson | US-Belgium | Ad26.COV2.S | Ad26 | No | Yes | Yes | 72 | 1 | 0 | -20 | 10.00 | 3.965 | 21 | Yes | 8.775 | No | Yes |
| Novavax | Russia | NVX-CoV2373 | Protein | No | No | No | 90.40 | 2 | 3 | Refrigerator | 3.00 | 3.890 | 24 | Yes | 10.828 | No | No |
| Sinopharm | China | BBIBP-CorV | Inactivated | Yes | Yes | Yes | 78.10 | 2 | 3 | N/A | 29.75 | 3.610 | 30 | No | 1.423 | No | No |
| Sinovac | China | CoronaVac | Inactivated | Yes | Yes | Yes | 50.65 | 2 | 2 | Refrigerator | 14.49 | 3.610 | 30 | No | 2.961 | Yes | No |
| Sinopharm-Wuhan | China | N/A | Inactivated | Yes | Yes | No | 72.80 | N/A | N/A | N/A | N/A | 3.610 | 30 | No | 1.423 | No | No |
| Bharat Biotech | India | Covaxin | Inactivated | No | Yes | No | 78 | 2 | 4 | Room temperature | 15.00 | 3.180 | 30 | No | 1.525 | No | No |
| Vector Institute | Russia | EpiVacCorona | Protein | Yes | Yes | No | N/A | 2 | 3 | Refrigerator | 5.51 | 2.760 | 24 | No | 0.055 | No | No |

**Table 2. Quantified data for the vaccines by category**

| Number | Developer | Approved | Emergency Use | Emergency Use by WHO | Efficacy Rate (%) | Dose | Weeks | Storage | Price (USD) | Logistics | Safety/ Reactogenicity | Variants | Market Share (%) | Children | Stopped Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Pfizer-BioNTech | 1 | 1 | 1 | 91.30 | 2 | 3 | -70 | 19.50 | 4.045 | 24 | 1 | 27.525 | 1 | 0 |
| 2 | Moderna | 1 | 1 | 1 | 92.50 | 2 | 4 | -32,5 | 15.00 | 3.890 | 24 | 1 | 10.040 | 1 | 0 |
| 3 | Gamaleya | 0 | 1 | 0 | 91.60 | 2 | 3 | 5 | 16.29 | 2.760 | 21 | 0 | 4.625 | 0 | 0 |
| 4 | Oxford-AstraZeneca | 1 | 1 | 1 | 76 | 2 | 4 | 5 | 4.00 | 4.020 | 21 | 1 | 17.068 | 0 | 1 |
| 5 | CanSino | 1 | 1 | 0 | 65.28 | 1 | 0 | 5 | 15.00 | 3.610 | 21 | 0 | 0.401 | 0 | 0 |
| 6 | Johnson & Johnson | 0 | 1 | 1 | 72 | 1 | 0 | -20 | 10.00 | 3.965 | 21 | 1 | 8.775 | 0 | 1 |
| 7 | Novavax | 0 | 0 | 0 | 90.40 | 2 | 3 | 5 | 3.00 | 3.890 | 24 | 1 | 10.828 | 0 | 0 |
| 8 | Sinopharm | 1 | 1 | 1 | 78.10 | 2 | 3 | 5 | 29.75 | 3.610 | 30 | 0 | 1.423 | 0 | 0 |
| 9 | Sinovac | 1 | 1 | 1 | 50.65 | 2 | 2 | 5 | 14.49 | 3.610 | 30 | 0 | 2.961 | 1 | 0 |
| 10 | Sinopharm-Wuhan | 1 | 1 | 0 | 72.80 | 2 | 3 | 5 | 29.75 | 3.610 | 30 | 0 | 1.423 | 0 | 0 |
| 11 | Bharat Biotech | 0 | 1 | 0 | 78 | 2 | 4 | 22,5 | 15.00 | 3.180 | 30 | 0 | 1.525 | 0 | 0 |
| 12 | Vector Institute | 1 | 1 | 0 | 78 | 2 | 3 | 5 | 5.51 | 2.760 | 24 | 0 | 0.055 | 0 | 0 |

### *3.4.2. Analysis: Grey Systems Theoretic Ranking Approach*

Once the data is quantified and prepared for the grey relational analysis as shown in Table 2, we implement our approach for the comparison, rating and ranking of the vaccines. Taking the data of Table 2 into account, the GRA procedure is as follows;

#### *3.4.2.1.Grey relational generating*

The main effort of grey relational generating is transforming the data into comparability sequences, in other words, a normalization of the data in different ranges and units into $[0,1]$ to form a comparable standard outlet. The Approved, Emergency Use, WHO's Emergency Use, Efficacy Rate, Logistics, Safety/Reactogenicity, Variants, Market Share and Children are of "the larger, the-better" attributes and hence are normalized using Eq. 1. The attributes of Dose, Weeks, Price and Stopped are type of "the smaller, the better" attributes. Those are normalized using Eq. 2. The only attribute Storage is of "the closer to the desired value $y_j^*$, the better" where $y_7^* = 5$, and is normalized using Eq. 3. The entire results of grey relational generating and the reference sequence $X_0$ are presented in Table 3.

**Table 3. Grey relational generating**

| Number | Developer | Approved | Emergency Use | Emergency Use by WHO | Efficacy Rate (%) | Dose | Weeks | Storage | Price (USD) | Logistics | Safety/ Reactogenicity | Variants | Market Share (%) | Children | Stopped Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | $X_0$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| 1 | Pfizer-BioNTech | 1.000 | 1.000 | 1.000 | 0.971 | 0.000 | 0.250 | 0.000 | 0.383 | 1.000 | 0.333 | 1.000 | 1.000 | 1.000 | 1.000 |
| 2 | Moderna | 1.000 | 1.000 | 1.000 | 1.000 | 0.000 | 0.000 | 0.500 | 0.551 | 0.879 | 0.333 | 1.000 | 0.364 | 1.000 | 1.000 |
| 3 | Gamaleya | 0.000 | 1.000 | 0.000 | 0.978 | 0.000 | 0.250 | 1.000 | 0.503 | 0.000 | 0.000 | 0.000 | 0.166 | 0.000 | 1.000 |
| 4 | Oxford-AstraZeneca | 1.000 | 1.000 | 1.000 | 0.606 | 0.000 | 0.000 | 1.000 | 0.963 | 0.981 | 0.000 | 1.000 | 0.619 | 0.000 | 0.000 |
| 5 | CanSino | 1.000 | 1.000 | 0.000 | 0.350 | 1.000 | 1.000 | 1.000 | 0.551 | 0.661 | 0.000 | 0.000 | 0.013 | 0.000 | 1.000 |
| 6 | Johnson & Johnson | 0.000 | 1.000 | 1.000 | 0.510 | 1.000 | 1.000 | 0.667 | 0.738 | 0.938 | 0.000 | 1.000 | 0.317 | 0.000 | 0.000 |
| 7 | Novavax | 0.000 | 0.000 | 0.000 | 0.950 | 0.000 | 0.250 | 1.000 | 1.000 | 0.879 | 0.333 | 1.000 | 0.392 | 0.000 | 1.000 |
| 8 | Sinopharm | 1.000 | 1.000 | 1.000 | 0.656 | 0.000 | 0.250 | 1.000 | 0.000 | 0.661 | 1.000 | 0.000 | 0.050 | 0.000 | 1.000 |
| 9 | Sinovac | 1.000 | 1.000 | 1.000 | 0.000 | 0.000 | 0.500 | 1.000 | 0.570 | 0.661 | 1.000 | 0.000 | 0.106 | 1.000 | 1.000 |
| 10 | Sinopharm-Wuhan | 1.000 | 1.000 | 0.000 | 0.529 | 0.000 | 0.250 | 1.000 | 0.000 | 0.661 | 1.000 | 0.000 | 0.050 | 0.000 | 1.000 |
| 11 | Bharat Biotech | 0.000 | 1.000 | 0.000 | 0.654 | 0.000 | 0.000 | 0.767 | 0.551 | 0.327 | 1.000 | 0.000 | 0.054 | 0.000 | 1.000 |
| 12 | Vector Institute | 1.000 | 1.000 | 0.000 | 0.654 | 0.000 | 0.250 | 1.000 | 0.906 | 0.000 | 0.333 | 0.000 | 0.000 | 0.000 | 1.000 |

*3.4.2.2.Calculating grey relational coefficient*

As the reference sequence $X_0$ is also included in Table 3, we calculate grey relational coefficients using Eq. 4. As discussed earlier, we consider the distinguishing coefficient $\zeta = 0.5$ as common selection in the literature. It should be highlighted that any arbitrary selection of the distinguishing coefficient does not change the rank order of the grey relational coefficients. All calculated grey relational coefficients are given in Table 4 in which the weights of attributes $w_j$'s are also included. We evaluate the importance and priority all attributes are equal, i.e., equally weighted and nonpreemptive, and hence, we specify $w_j = {}^{1}/_{n} = {}^{1}/_{14} = 0.071$ to be used in the following step.

**Table 4. Grey relational coefficients**

| Number | Developer | Approved | Emergency Use | Emergency Use by WHO | Efficacy Rate (%) | Dose | Weeks | Storage | Price (USD) | Logistics | Safety/ Reactogenicity | Variants | Market Share (%) | Children | Stopped Use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Pfizer-BioNTech | 1.000 | 1.000 | 1.000 | 0.946 | 0.333 | 0.400 | 0.333 | 0.448 | 1.000 | 0.429 | 1.000 | 1.000 | 1.000 | 1,000 |
| 2 | Moderna | 1.000 | 1.000 | 1.000 | 1.000 | 0.333 | 0.333 | 0.500 | 0.527 | 0.806 | 0.429 | 1.000 | 0.440 | 1.000 | 1,000 |
| 3 | Gamaleya | 0.333 | 1.000 | 0.333 | 0.959 | 0.333 | 0.400 | 1.000 | 0.502 | 0.333 | 0.333 | 0.333 | 0.375 | 0.333 | 1,000 |
| 4 | Oxford-AstraZeneca | 1.000 | 1.000 | 1.000 | 0.559 | 0.333 | 0.333 | 1.000 | 0.930 | 0.963 | 0.333 | 1.000 | 0.568 | 0.333 | 0,333 |
| 5 | CanSino | 1.000 | 1.000 | 0.333 | 0.435 | 1.000 | 1.000 | 1.000 | 0.527 | 0.596 | 0.333 | 0.333 | 0.336 | 0.333 | 1,000 |
| 6 | Johnson & Johnson | 0.333 | 1.000 | 1.000 | 0.505 | 1.000 | 1.000 | 0.600 | 0.656 | 0.889 | 0.333 | 1.000 | 0.423 | 0.333 | 0,333 |
| 7 | Novavax | 0.333 | 0.333 | 0.333 | 0.909 | 0.333 | 0.400 | 1.000 | 1.000 | 0.806 | 0.429 | 1.000 | 0.451 | 0.333 | 1,000 |
| 8 | Sinopharm | 1.000 | 1.000 | 1.000 | 0.592 | 0.333 | 0.400 | 1.000 | 0.333 | 0.596 | 1.000 | 0.333 | 0.345 | 0.333 | 1,000 |
| 9 | Sinovac | 1.000 | 1.000 | 1.000 | 0.333 | 0.333 | 0.500 | 1.000 | 0.538 | 0.596 | 1.000 | 0.333 | 0.359 | 1.000 | 1,000 |
| 10 | Sinopharm-Wuhan | 1.000 | 1.000 | 0.333 | 0.515 | 0.333 | 0.400 | 1.000 | 0.333 | 0.596 | 1.000 | 0.333 | 0.345 | 0.333 | 1,000 |
| 11 | Bharat Biotech | 0.333 | 1.000 | 0.333 | 0.591 | 0.333 | 0.333 | 0.682 | 0.527 | 0.426 | 1.000 | 0.333 | 0.346 | 0.333 | 1,000 |
| 12 | Vector Institute | 1.000 | 1.000 | 0.333 | 0.591 | 0.333 | 0.400 | 1.000 | 0.842 | 0.333 | 0.429 | 0.333 | 0.333 | 0.333 | 1,000 |
| | **Weights** | 0,071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 | 0.071 |

*3.4.2.3.Obtaining grey relational grade*

After determining the weight of attributes and all grey relational coefficients, we finally obtain grey relational grades using Eq. 5. They are indeed weighted mean of grey relational coefficients for each vaccine. The entire grey relational grades of each vaccine are presented in Table 5. These are indeed ratings of the SARS-CoV-2 vaccines obtained from grey systems theory, particularly grey relational analysis.

**Table 5. Grey relational grades**

| Number | Developer | Grey Relational Grade |
|---|---|---|
| 1 | Pfizer-BioNTech | 0.7778 |
| 2 | Moderna | 0.7406 |
| 3 | Gamaleya | 0.5406 |
| 4 | Oxford-AstraZeneca | 0.6919 |
| 5 | CanSino | 0.6591 |
| 6 | Johnson & Johnson | 0.6719 |
| 7 | Novavax | 0.6186 |
| 8 | Sinopharm | 0.6619 |
| 9 | Sinovac | 0.7138 |
| 10 | Sinopharm-Wuhan | 0.6088 |
| 11 | Bharat Biotech | 0.5408 |
| 12 | Vector Institute | 0.5901 |

## 4. Results

As all grey relational grades that are overall performance scores of the vaccines along attributes are obtained, shown in Table 5, we get an overall ranking (ratings) of SARS-CoV-2 vaccines, which is tabulated in Table 6. The ranking is calculated based on the assumption of equal importance and priority of 14 attributes.

**Table 6. The ranking of SARS-CoV-2 vaccines with respect to equally weighted attributes**

| Number | Developer | Grey Relational Grade |
|---|---|---|
| 1 | Pfizer-BioNTech | 0.7778 |
| 2 | Moderna | 0.7406 |
| 3 | Sinovac | 0.7138 |
| 4 | Oxford-AstraZeneca | 0.6919 |
| 5 | Johnson & Johnson | 0.6719 |
| 6 | Sinopharm | 0.6619 |
| 7 | CanSino | 0.6591 |
| 8 | Novavax | 0.6186 |
| 9 | Sinopharm-Wuhan | 0.6088 |
| 10 | Vector Institute | 0.5901 |
| 11 | Bharat Biotech | 0.5408 |
| 12 | Gamaleya | 0.5406 |

According to the COVID-19 vaccines ranking results based on the assumption that all attributes are assumed to be equally important and preemptive, the range of the grey relational grades is 0.2371 varies between 0.5406 and 0.7778. The median is 0.6605, and the mean is 0.6513 with a standard deviation of 0.0714.

As the details are seen in Table 6, the Pfizer/BioNTech vaccine is at the top rank with a grey relational grade of 0.7778. The second rank belongs to Moderna with 0.7406 when the third belongs to Sinovac 0.7138. The top three are followed Oxford-AstraZeneca, Johnson & Johnson, Sinopharm, and others.

In comparison of vaccine platforms, the mean of grey relational grades of the mRNA platform vaccines Pfizer/BioNTech and Moderna is 0.7591, that is, the mRNA platform produces the best performance. The second best platform is the viral vector platform with a mean grey relational grade of 0.6408. The third performance belongs to the inactivated virus platform with 0.6313. The protein platform is the at the last rank with a mean grey relational grade of 0.6043.

We generate the grey systems theoretic ranking of SARS-CoV-2 vaccines, in which all attributes are assumed to be equally important and preemptive. Other different rankings may also be obtained with different importance and priorities, for instance, one can give higher importance of the attributes Efficacy Rate, Variants and Children, respectively, by just easily rearranging the attribute weights to sum up to 1. The higher weight means the related attribute has higher importance or priority.

As an instance, if we weight the Efficacy Rate attribute by 40%, and the other remaining 13 attributes by 60%, the new ranking becomes as seen in Table 7.

**Table 7. The ranking of SARS-CoV-2 vaccines with respect to 40% weighted Efficacy Rate**

| Number | Developer | Grey Relational Grade |
|---|---|---|
| 1 | Pfizer-BioNTech | 0.8372 |
| 2 | Moderna | 0.8324 |
| 3 | Novavax | 0.7213 |
| 4 | Gamaleya | 0.6886 |
| 5 | Oxford-AstraZeneca | 0.6449 |
| 6 | Sinopharm | 0.6373 |
| 7 | Johnson & Johnson | 0.6129 |
| 8 | Vector Institute | 0.5903 |
| 9 | CanSino | 0.5797 |
| 10 | Sinovac | 0.5792 |
| 11 | Sinopharm-Wuhan | 0.5756 |
| 12 | Bharat Biotech | 0.5585 |

According to the new ranking, in which the Efficacy Rate is weighted by 40%, Pfizer/BioNTech ranks again number 1, Moderna does number 2, which is followed by Novavax at the third rank. The details are presented in Table 7.

If the sample size of the vaccines, 12, would allow us, we would have done further statistical analyses using grey relational coefficients (Table 4) and grey relational grades (Table 5) such as ANOVA, dimension reduction and principal component analysis under related certain assumptions. However, the sample size does not allow us for further reasonable statistical investigation.

## 5. Discussion

We suggest the use of grey systems theory, particularly grey relational analysis, to obtain a comparison, rating, and ranking frame of SARS-CoV-2 vaccines and vaccine platforms in appropriate attributes. We select 12 leading vaccines and their related 14 distinguishing attributes (or performance criteria). In addition to clinical attributes, we cover some authorization criteria including different approvals and accreditations, and accessibility attributes such as price, logistics, and market share as well as important criteria for protection against variants and children use to form a 360 degree feedback frame. The engine of our frame converting attributes to ratings and grades is grey relational analysis.

Our proposed grey systems theoretic ranking approach, which is unbiased and reproducible, is based on the objective attributes rather than subjective judgements and experiences that are not exactly reproducible. Moreover, the frame is user friendly, once the model is built on a spreadsheet, it may be re-run by just updating the new data to produce new rating and rankings. Furthermore, the weights of attributes may also be specified by an expert panel using a multi-attribute decision making techniques such as Analytical Hierarchy Process (AHP).

It is also remarkable that we suggest the use of a Wuhan-originated tool, grey systems theory which has spread like a very-useful-pandemic for almost 40 years, to compare, rate and rank the vaccines to fight another Wuhan-originated agent, coronavirus pandemic.

As a future research, our proposed grey systems theoretic ranking approach may be used with finite number of vaccines ($m$) and attributes ($n$). That means the size of the frame or model depends on the researchers. In this case, with larger sample sizes, further statistical analyses may be implemented. Our limitation is that there are full reliable data for all 14 attributes only for 12 leading vaccines.

Moreover, it has been demonstrated that heterologous vaccine regimens, that is, mixing COVID-19 vaccines has good immune response, as an instance, Borobia et.al., (2021) recently finds Pfizer/BioNTech given as a second dose in individuals prime vaccinated with Oxford-AstraZeneca induced a robust immune response. Some heterologous vaccine regimens (eg, Oxford-AstraZeneca + Pfizer/BioNTech) may be considered as an additional hybrid vaccine to be included in our grey systems theoretic ranking as long as the relevant data emerges as another future research.

What is more, as a further study, the grey system theoretic frame can be employed for any kind of vaccines and/or clinical agents in any subject category and related attributes (or performance criteria). As an instance, some chemotherapeutic agents may be compared, rated, and ranked with respect to relevant attributes as a multi attribute decision making tool. In general, such an effort may be entitled *Clinical Agents Ranking Frame* (CARF).

Although we rate and rank COVID-19 vaccines, all vaccines and vaccine working are valuable, particularly in this difficult time of shortage and inadequate global accessibility of the vaccines. Our effort is to determine the primus inter pares (= first among equals). The best vaccine is the one that you are able to get as the most effective weapon against SARS-CoV-2. Do not mind the gap!

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## CONFLICT OF 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.