Assessing inequities in COVID-19 vaccine roll-out strategy programs: a cross-country study using a machine learning approach

Mehrdad Kazemi[1], Nicola Luigi Bragazzi[1†], Jude Kong[1†,*]

[1] Africa-Canada Artificial Intelligence and Data Innovation Consortium (ACADIC), Department of Mathematics and Statistics, Faculty of Science, York University, Toronto, ON, Canada

[†]Co-last authors

[*]Corresponding author's email: jdkong@yorku.ca

Abstract

Background: After the start of the COVID-19 pandemic and its spread across the world, countries have adopted containment measures to stop its transmission, limit fatalities and relieve hospitals from strain and overwhelming imposed by the virus. Many countries implemented social distancing and lockdown strategies that negatively impacted their economies and the psychological wellbeing of their citizens, even though they contributed to saving lives. Recently approved and available, COVID-19 vaccines can provide a really viable and sustainable option for controlling the pandemic. However, their uptake represents a global challenge, due to vaccine hesitancy logistic-organizational hurdles that have made its distribution stagnant in several developed countries despite several appeal by the media, policy- and decision-makers, and community leaders. Vaccine distribution is a concern also in developing countries, where there is scarcity of doses.

Objective: To set up a metric to assess vaccination uptake and identify national socio-economic factors influencing this indicator.

Methods: We conducted a cross-country study. We first estimated the vaccination uptake rate across countries by fitting a logistic model to reported daily case numbers. Using the uptake rate, we estimated the vaccine roll-out index. Next, we used Random Forest, an "off-the-shelf" machine learning algorithm, to study the association between vaccination uptake rate and socio-economic factors.

Results: We found that the mean vaccine roll-out index is 0.016 (standard deviation 0.016), with a range between 0.0001 (Haiti) and 0.0829 (Mongolia). The top four factors associated with vaccine roll-out index are the median *per capita* income, human development index, percentage of individuals who have used the internet in the last three months, and health expenditure *per capita*.

Conclusion: The still ongoing COVID-19 pandemic has shed light on the chronic inequality in global health systems. The disparity in vaccine adoption across low- and high-income countries is a global public health challenge. We must pave the way for a universal access to vaccines and other approved treatments, regardless of demographic structures and underlying health conditions. Income disparity remains, instead, an important cause of vaccine inequity, and the tendency toward "vaccine nationalism" and “vaccine apartheid” restricts the functioning of the global vaccine allocation framework and, thus, the ending of the pandemic. Stronger mechanisms are needed to foster countries' political willingness to promote vaccine and drug access equity in a globalized society, where future pandemics and other global health rises can be anticipated.

Keywords: COVID-19; pandemic; vaccine roll-out; vaccine nationalism; cross-country analysis; machine learning; Random Forest

Introduction

Since its initial outbreak in late December 2019, the still ongoing “Coronavirus disease 2019” (COVID-19) pandemic, caused by the infectious agent known as “Severe Acute Respiratory Syndrome-related Coronavirus type 2” (SARS-CoV-2), has been representing a true global public health challenge [1]. Due to the emerging nature of the pathogen, against which populations were largely immunologically naïve, its highly contagious and quick spreading, healthcare facilities have been dramatically overwhelmed by a considerably high toll of infections [2]. To contain the virus and to counteract this unprecedented strain, countries have implemented non-pharmaceutical interventions (NPIs), like enhanced hygiene practices, social distancing, self-isolation, quarantine and even lockdown of entire territories [3].

Differently from the early phases and waves when the entire world was completely unprepared to tackle the outbreak and NPIs were the only possible strategy to implement, as of today several vaccines have been approved and are available. While NPIs, despite being effective in flattening the epidemic curve and curbing cases and deaths, are not sustainable in the long-period, COVID-19 vaccines can provide a really viable option and strategy for controlling the pandemic [4].

However, despite vaccines’ excellent effectiveness and safety profiles [5], mass immunization campaigns are successful only when vaccine uptake rate is satisfactorily high, ensuring the achievement of herd immunity. This can, on the one hand, control the viral transmission dynamics and, on the other hand, confer immune protection to those frail subjects who, although being willing, are unable to vaccinate against COVID-19, because their status of immune deficiency or suppression does not enable them to build up sufficiently robust immunity levels. Besides clinical reasons, other factors, such as lack of confidence towards science and vaccination, false beliefs regarding the severity of COVID-19 and/or the efficacy of vaccines, and perceived barriers to immunization, can jeopardize the implementation of mass vaccination campaigns, thus posing serious health risks. Indeed, the World Health Organization (WHO) defines vaccine acceptance as one of the major challenges to global public health [6].

Vaccine hesitancy is a complex, multi-factorial phenomenon, which results by the subtle, non-linear interplay among various parameters, ranging from socio-economic and educational variables to behavioral ones [7-9].

Specifically concerning COVID-19, this pandemic has been affecting more than 220 countries and territories. This has significantly impacted the chains and procedures of drugs and in particular vaccines supply, logistics, and distribution [10].

While many high-income countries have already started implementing immunization campaigns, securing for themselves more than half of the world's available doses of COVID-19 vaccines, most developing countries, including African nations, are still waiting for vaccine stocks while preparing their vaccination campaigns [11]. "Vaccine nationalism" by economically developed nations is contributing to shape vaccine scarcity in poor nations, which have to rely mainly on global collaborative co-financing vaccine procurement mechanisms, such as the COVID-19 Vaccines Global Access (COVAX) and the World Bank and the African Union's Covid-19 Africa Vaccine Acquisition Task Team (AVATT) platforms, aimed at supporting equitable and sustainable access to COVID-19 vaccines [12].

To quantitatively assess inequities in vaccine allocation, distribution, and uptake at the global level, we conducted this cross-country study, employing machine learning techniques to assist and inform the modelling of non-linearity underlying the phenomenon of vaccine hesitancy. As such, this study can have important practical implication for global and public health workers, decision- and policy-makers, and all relevant stakeholders involved in vaccine roll-out strategy programs.

Methods

Estimating the vaccination uptake rate among different countries

First, we computed the vaccination uptake rate across different countries. Since the growth of cumulative given doses is qualitatively similar to a logistic function which grows exponentially at first but slows as it proceeds reaching a plateau eventually (Fig 1), the logistic growth model was used to estimate vaccination uptake rate. In the logistic model, the cumulative number of doses administered *c(t)* satisfies the following equation:

$$c(t) = \frac{K}{1 + ae^{-rt}}$$

Where K is the total number of doses administered at the end of the vaccination campaign, r the vaccination uptake rate, and $\frac{K}{1+a} = c(0)$ the initial number of doses given. To estimate r, the least square fitting algorithm was employed through Python's SciPy *curvefit()* function to fit the rate of change in cumulative cases of a logistic growth model to daily given doses based on the data from [13].

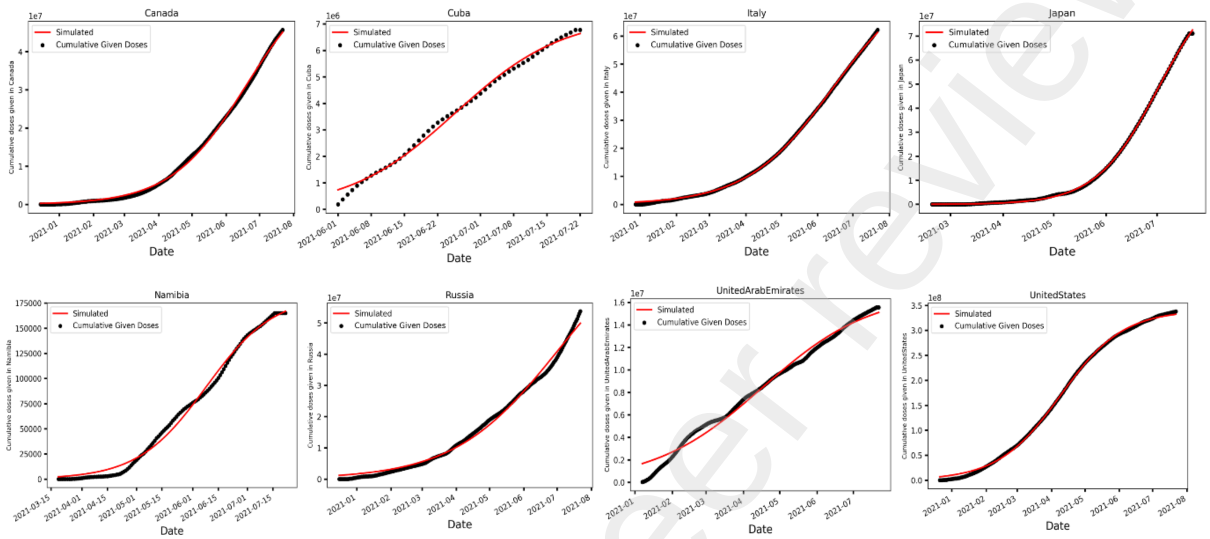

***Figure 1**.Dots represent cumulative given doses, and curves are fitted based on the logistic growth model. Countries are sorted alphabetically. The average of R^2 across all countries is 0.99.*

Vaccine Roll-out Index (VRI)

Next, we defined the Vaccine Roll-out Index (VRI) for a country as follows:

$$VRI = r \times \frac{d}{N}$$

Where *r* is the vaccination uptake rate as defined in the previous paragraph, *d* the total number of given doses, and *N* the population. VRI was used as an index to compare the overall vaccination adoption among different countries as it reflects both the speed and the extent of mass vaccination in a country. For instance, Haiti has the highest vaccination uptake rate (0.39) among all the countries compared. However, when it comes to the extent of vaccination campaign or $\frac{d}{N}$, it comes last (0.0004). This extreme example illustrates the importance of both speed and extent in shaping a successful vaccination campaign. For each country VRI was calculated based on the estimated *r* values and publicly available data [14] for $\frac{d}{N}$.

Covariates

Next, through a comprehensive literature review and assessment [15,16], critical thinking and consultations with experts, 35 covariates from seven different categories (demographic, disease, economics, environmental, habitat, health, and social) were chosen as predictors for VRI. To the best of our knowledge, this number of covariates is unprecedented in the literature since many similar studies have used few covariates. Moreover, these studies employed linear regression. However, due to the use of Random Forest (RF) algorithm, we were able to include non-linear covariates as well, since, as previously mentioned, vaccine hesitancy is a complex, multi-factorial, non-linear phenomenon.

We built a data set with 142 countries accounting for 95% of the world's population. We collected the most recent available data on the chosen covariates from publicly available databases. We selected diverse, specific covariates that are comparable across countries. For instance, nurses *per capita* was favored over doctors *per capita* since healthcare systems vary among countries and nurses are the primary care provider in many countries. Also, for a better comparison we divided absolute numbers by total population to get *per capita* numbers. To deal with missing data, for each covariate we used Classification And Regression Trees (CART) algorithm to estimate missing data based on the other covariates. Below is the table of all the covariates used in this study with their explanations and sources.

Category	Covariate	Source
Demographic	Youth: Population ages 20–35 (% of total population)	17
Demographic	Total Pop: Population total	17
Demographic	Population density	17
Demographic	Median age	18
Demographic	Aged 65 older	17
Disease	Mort Resp: Mortality rate from lower respiratory	19

	infections (per 100,000)	
Disease	Mortality rate from infectious and parasitic diseases (per 100,000)	19
Economic	GINI: GINI index	20
Economic	Ease of doing business index 2019 (1 = most business-friendly regulation)	21
Economic	GDP per capita	17
Economic	Extreme poverty (Share of the population living in extreme poverty, most recent year available since 2010)	17
Habitat	Population in urban agglomerations of more than 1 million (% of total population)	17

Habitat	Urban population (% of total population)	17
Health	GHS: Global Health Security detection index	22
Health	Nurses: Nurses and midwives (per 1,000 people)	17
Social	Social Media: Average People's Use Of Social Media To Organize Offline Action (4 = high)	23
Social	Internet Filtering: Government Internet filtering in practice (4 = low)	23
Social	Air Transport: passengers carried per capita	17
Health-Social	life expectancy (Life expectancy at birth in 2019)	24
Composite index(Economic-Social-	Human development index	14

Health-Education)		
Health	Stringency index	25
Health	Total deaths attributed to COVID-19 per 1,000,000 people	26
Demographic	Rural population	27
Health	Type of vaccine	13
Demographic	Gender ratio	28
Health	Health expenditure per capita, PPP	29
Health	Share of population covered by health insurance	30
Health	Cardiovascular disease death rate (per 100,000)	31
Education	Literacy rate (percentage of people ages 15 and above)	17
Technology	Individuals using the Internet (% of population)	17

Demographic	Average household size (number of members)	18
Economic	Median per-capita Income	32
Economic	Unemployment, total (% of total labor force)	33
Education	School enrollment, tertiary (% gross)	34
Health	Years of health lost due to disability (YLD)	35

Random Forest regression analysis of the association between covariates and VRI

Random Forest (RF), an "off-the-shelf" machine learning algorithm, was used to determine associations between predictors and VRI. Random forest is a collection of decision trees where each tree depends on the value of an independently sampled vector chosen randomly (Breiman, 2001). For regression, RF implements a combination of de-correlated decision trees and declares the final output as the average of all predictions made by trees. As opposed to the prevalent literature, we decided to use RF for modeling as it has many advantages that makes it a perfect fit for this type of data analysis. Such advantages include [36]:

- Can capture non-linear relationships between features and the target variable
- Less sensitive to outliers
- No need to prune the decision trees (overcoming the issue of overfitting)
- The importance of each covariate can be numerically measured
- Can handle continuous, categorical, and binary data

Among all these advantages, the ability to capture non-linear relationships between features and the target variable is crucially important for this study. Non-linear relationships between variables is a common feature of many datasets. For instance, below is the plot of literacy rate versus VRI which clearly does not show a linear pattern.

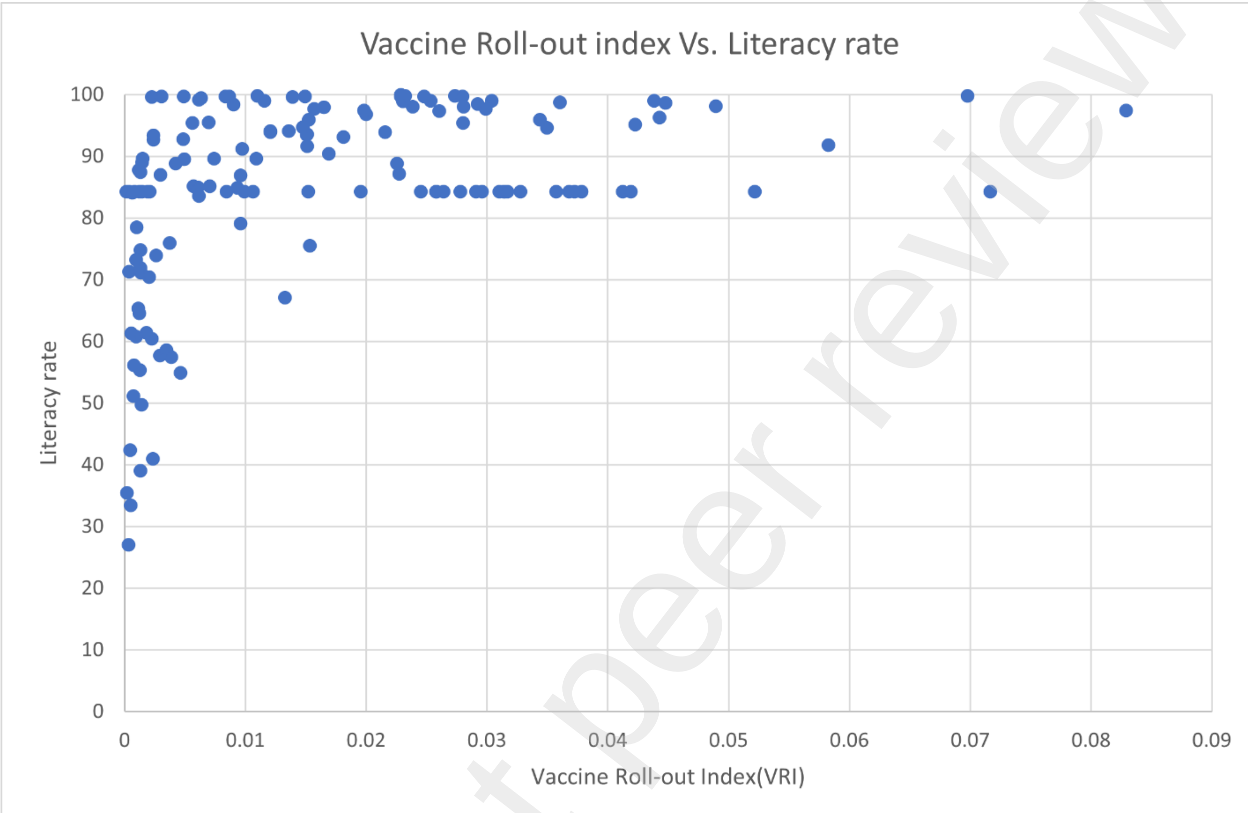

Figure 2. Vaccine Roll-out Index (VRI) versus Literacy rate (Adult literacy rate is the percentage of people ages 15 and above who can both read and write with understanding a short simple statement about their everyday life)

We used the “RandomForestRegressor" module in the Python Scikit-learn library to build 500 decision trees where for each tree, square root of the total number of covariates were chosen randomly to make splits [37]. Also, the maximum depth of each tree was obtained by 10-fold cross-validation. Since we were only interested in finding associations between covariates and the target variable, we used all the data as the training data. To assess the contribution of each covariate to the model fitting, we implemented [38]'s permutation-based measures. This method considers a feature to be important if shuffling its values increases the model error, and unimportant if it does not change the model error much.

Evaluation metrics

In terms of evaluation, we used the mean squared error (MSE) and the coefficient of determination R^2. MSE measures how close a prediction is to the observed value and is given by the formula:

$$\frac{1}{n}\sum_{i=1}^{n}(y_i - \widehat{y_l})^2$$

Where n is the sample size, y_i is the observed value and $\widehat{y_l}$ is the predicted one; R^2 is given by the formula:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \widehat{y_l})^2}{\sum_{i=1}^{n}(y_i - \overline{y_n})^2}$$

Where $\overline{y_n}$ is the average of the observed values. R^2 represents the proportion of the dependant variable's variance that is explained by independent variables in the model. For our model, which was trained using all the data only to find associations, $MSE = 0.00002$ and $R^2 = 0.93$ which approve the validity of our approach.

Results

Estimation of COVID-19 Vaccination uptake rate among countries

Fig 1 and [F1] show vaccination uptake curves fitted to observed time series in daily given doses across studied countries. [S1] provides the estimated vaccination uptake rate across studied countries. For 142 countries considered, the average of R^2 is 0.99 and vaccination uptake rate is highest in Haiti, Algeria, and Madagascar with 0.395, 0.239 and 0.173, respectively, and lowest in Turkey, Indonesia and Eswatini with 0.0144, 0.0206 and 0.0208, respectively. Overall, the average of vaccination uptake rate was found to be 0.046 with a standard deviation of 0.042. Moldova (0.04635), Vietnam (0.0464) and Georgia (0.045) are the closest to the mean.

Vaccine Roll-out index (VRI) among countries

Fig 3 and [S2] summarize the value of VRI for countries studied. For 142 countries considered, VRI is highest in Mongolia (0.083), Israel (0.072) and Cuba (0.070) and lowest in Haiti (0.00014), Chad (0.00021) and South Sudan (0.00034). The mean VRI is 0.016 with a standard deviation of 0.016. Romania, Argentina, and Comoros are the closest to the mean with 0.0157, 0.0165 and 0.0153, respectively. Although it is counterintuitive that a developing country is leading, Mongolia has reportedly emerged as a positive outlier [39,40,41]. Due to its unique geopolitical situation, the country has been able to receive vaccine from its powerful neighbours China and Russia [39,40,41]. Moreover, as a developing country Mongolia has received doses from COVAX as well [41].

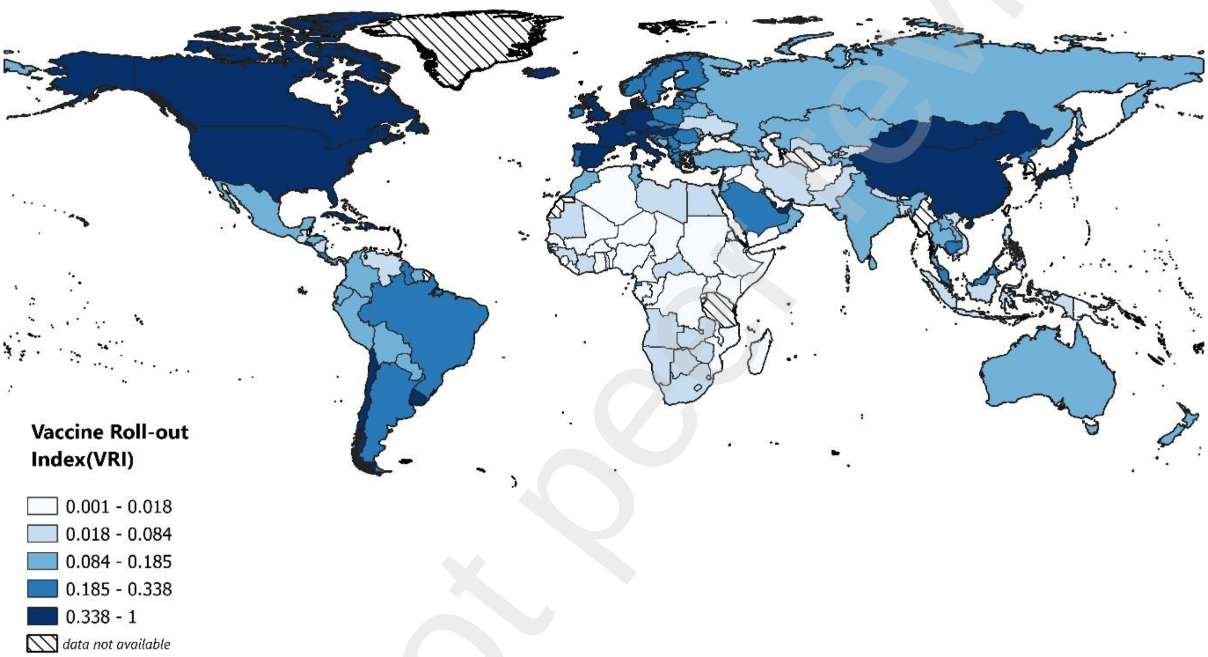

***Figure 3**. Heatmap of studied countries. They are coloured based on their Vaccine Roll-out Index(VRI) value. All VRI values were multiplied by a constant to be in the range of 0 to 1. Five intervals were selected such that the number of countries in each one be the same.*

Association between predictors and VRI

Fig 3 indicates that i) median *per capita* income, ii) human development index, iii) percentage of individuals who have used the internet in the last three months (latest data available) via a computer, mobile phone, personal digital assistant, games machine, digital TV, etc., and iv) health expenditure *per capita* are the four most important covariates associated with the Vaccine Roll-out Index (VRI).

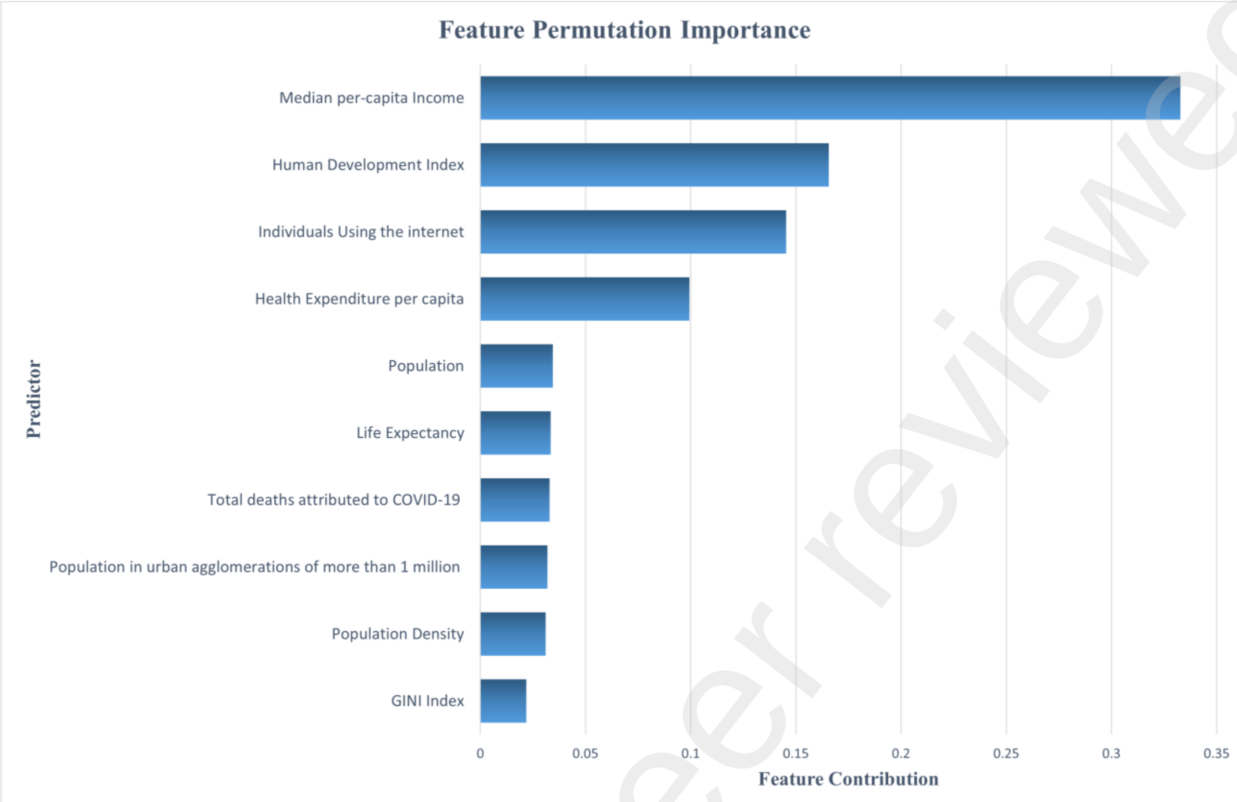

Figure 4. Top ten covariates with the highest Permutation Feature Importance. i) median per capita income, ii) human development index, iii) percentage of individuals who have used the internet in the last three months (latest data available) via a computer, mobile phone, personal digital assistant, games machine, digital TV, etc., and iv) health expenditure per capita. Also, the results illustrate that other covariates, particularly the type of vaccine do not play a key role.

Discussion

The present study has shown that i) median *per capita* income, ii) human development index, iii) percentage of individuals who have used the internet in the last three months via a computer, mobile phone, personal digital assistant, games machine, digital TV, etc., and iv) health expenditure *per capita* are the four most important covariates associated with the Vaccine Roll-out Index (VRI). These findings are in line with those of previously studies [42,43]. More specifically, Duan et al. [42] carried out a cross-sectional ecological study and analyzed the association between country income level and COVID-19 vaccination coverage rates in 138 countries, in terms of the mediating role of vaccination policies. Authors devised a single-mediator model based on structural equation modeling. Authors found that, with respect to high-income countries, upper-middle-, lower-middle-, and low-income countries reported lower vaccination coverage rates. Immunization policies were found to mediate from 14.6% to 15.6% of coverage in upper-middle and lower-middle countries, respectively, whereas this effect was not statistically significant in low-income countries. Conclusions were similar when accounting for different country-related demographic and health parameters. Roghani and Panahi [43] quantitatively assessed the association of COVID-19 vaccine allocation and two major macro-socioeconomics measures, namely HDI and Gross domestic product (GDP), in 25 countries. Authors found a positive, statistically significant association between GDP *per capita* and COVID-19 vaccine distribution, while no link could be detected for HDI.

With respect to these two studies, our investigation is much broader and takes into account more countries and more covariates, utilizing a sophisticated machine learning approach, which enables to model the non-linearity underlying the phenomenon of vaccine hesitancy. However, despite some methodological differences, all this suggests that high-income countries, widely known as developed countries [44], are more likely to have higher COVID-19 vaccine adoption rates among all countries. This is precisely consistent with the way COVID-19 vaccination adoption has been unfolding worldwide.

By late April, more than 81% of the doses had been administered to people residing in high- and upper-middle-income countries, with only 0.3% being received by people in low-income countries [45]. In fact, economically developed countries have secured enough doses to vaccinate 245% of their adult populations [46]. As a result, low- and lower-middle-income countries can only cover around one third of their citizens with purchased doses [46]. Hence, it is no surprise that low-income countries cannot reach vaccination herd immunity until 2023, if at all [47]. Therefore, low-income nations are most likely to continue suffering from COVID-19 for a longer span of time compared to high-income countries [48]. COVID-19 vaccine allocation, distribution and deployment are significantly uneven with around 95% of the total doses being administered to only 20% of the global population [49]. The crude observation that in low-income countries, clinically vulnerable and frail individuals are dying from COVID-19 yet simultaneously, already fully vaccinated people are lining up to get their third dose in wealthy countries has been labeled as "vaccine apartheid" and "a catastrophic moral failure" by the director-general of the WHO, who has called for a moratorium in the administration of booster shots to help developing countries, which are struggling to vaccinate against COVID-19 (Cohen, 2021).

Ensuring that low-income countries have and sustainable access to COVID-19 vaccines should be regarded as a global responsibility and onus [50]. It must be noted that the challenge that developing countries are facing is not limited to vaccination but also in procuring other supplies such as chemical reagents necessary for testing for COVID-19, as well as approved drugs which were thought to be helpful in treating COVID-19 or at least mitigating against the severity of its symptoms [48]. In addition, even if a low-income country succeeded to purchase vaccine, they would face challenges to store and even administer the doses [48]. In fact, according to a recently published report from the World Bank, "vaccine preparedness" is a challenge in many low- and middle-income countries [51].

One of the main reasons why high-income countries can hoard vaccines through firsthand access, is due to their huge investments in vaccines development. For instance, the USA alone invested staggering US $6.577 billion in AstraZeneca, Johnson & Johnson/Janssen, Novavax, Moderna Inc., and Pfizer and BioNTech SE, to support their vaccine development plans [48]. This would have been too expensive for many developing countries. Based on a technical report [52], it needs about £2.5 million for Clinical Trial Phase I, £20 million for Clinical Trial Phase II, £65-250 million for Clinical Trial Phase III and £20 million for Phase IV. Adding it up, this number couldgo as high as £292.5 million.

The COVID-19 pandemic is a novel and unprecedented situation, but the inequality in access to vaccines as well as other healthcare provisions has been a common theme throughout many past pandemics and outbreaks. During the 2004 influenza A(H5N1) and 2009 influenza A (H1N1) pandemics, developed countries purchased most available vaccines leaving few doses available for developing countries [53,54,55]. Australia postponed the export of H1N1 vaccines [56], Canada and the USA withheld the doses until their domestic needs were met [48]. The same phenomenon happened during the 2009 swine flu pandemic [57]. For *Haemophilus influenzae* type b (Hib) vaccine to be introduced in Bangladesh, it took staggering 21 years since its first licensure in the USA [58]. Grown out of such bitter experiences, COVAX initiative, co-led by the Coalition for Epidemic Preparedness Innovations (CEPI), the Global Alliance for Vaccines and Immunisation (GAVI), and the WHO was formed with hopes to provide equitable access to COVID-19 vaccines for low- and middle-income countries [59]. As a first step, COVAX planned to vaccinate at least 20% of the people in 92 developing countries by the end of 2021 [60]. Although COVAX has reportedly mobilised high-income countries to commit to support [48], economically developed countries still own the majority of global vaccine purchases through paying them at higher prices. "There is a lake of vaccine out there, and COVAX is receiving drops", said Doctor Margaret Harris, Spokesperson of the WHO, and public health physician specialized in infectious outbreaks and emergency risk communications [61]. Soon enough, COVAX seemed to be an unreliable source of timely available vaccine for developing countries leaving everything, once again, to the country's income level to determine vaccine access [42]. However, it was already too late for developing countries to start negotiating bilateral deals with vaccine suppliers as developed countries had already pre-ordered almost all doses. As a result, even countries that could afford the budget were waitlisted.

The COVID-19 pandemic will continue to be a threat until every citizen is covered and fully immunized in both rich and poor nations [48]. Scientists have warned that unless eradicated, the pandemic will evolve into a pan-endemic infection with a probable resurgence as late as 2024 [62,63]. Biologically, along with this disparity in vaccine adoption across different countries, new vaccine-resistant variants of concern (VOCs) will continue to emerge which sequentially threaten high-income countries as well [58,64,65]. Therefore, completely ending the COVID-19 pandemic and recovering global economy call for global access to vaccines and other effective drugs [48,58,64] that should be considered as "global public goods" as opposed to treating vaccines as "private goods", which has resulted, as previously said, into "vaccine nationalism" and "vaccine apartheid". Some approaches to reduce the gap between low- and high-income countries vaccine adoption include but are not limited to bilateral and multilateral donations and charity, scaling-up of vaccine production and temporary waivers of intellectual property [48,58,66]. To vaccinate priority groups in all countries around the world, at least 1.3 billion doses are needed for 92 low- and middle-income countries members of the COVAX platform initiative [61]. Researchers and scholars from the Kaiser Family Foundation (KFF) have stated that, without redistribution and re-allocation of doses already purchased by economically developed countries and/or enhanced support for manufacturing or production of further additional doses, globally more than four in ten (41%) adults will not be able to be immunized, even after allocating all COVAX doses to low- and middle-income countries [46]. Lastly, since to end "vaccine nationalism" and "vaccine apartheid" the root causes of global health inequities must be the target to change [66], the findings of this study may greatly help policy- and decision-makers and stakeholders on their mission to decrease the tremendous inequality in vaccine adoption across different countries worldwide.

Our results reaffirm the current massive inequality in global health, deeply rooted in the unbalanced universal distribution of wealth. Also, interestingly the results point out that overall, the type of vaccine does not play a key role in vaccination adoption for many countries. A plausible interpretation of this could be that most people simply do not have a choice. In fact, as only 29.1% of the world has received at least one dose of COVID-19 vaccines, they would be lucky if they got one. One limitation of this study is that, due to limited available data on the panel of vaccines administered by each country, we did not consider the effectiveness of vaccines used by countries. In addition, for all countries we used the number of given doses divided by population in the formula of VRI. This assumes that all the vaccines used by a country need the same number of doses to reach their full effectiveness which is not the case with the Johnson & Johnson/Janssen vaccine, which is a single-dose vaccine product. The novelty and strength of our work reside in the use of RF to find associations which enabled us to include 35 covariates with both linear and non-linear relationship to the target variable. To the best of our knowledge, this method has never been used in previous studies making the insights from this research more valuable.

Conclusion

The still ongoing COVID-19 pandemic has shed light on the chronic inequality in global health systems. The disparity in vaccine adoption across low- and high-income countries is a challenge to the achievement of many global goals such as the "Sustainable Development Goal" (SDG) 3, concerning "Good Health and Well-being", which is one of the 17 SDGs established by the United Nations in 2015 [48]. Our investigation confirms that the median *per capita* income is the main contributor to the inequality in vaccine adoption across different countries. As a lesson learnt from this global crisis, we must pave the way for a universal access to vaccines and other approved treatments as mentioned in the SDG 3, regardless of demographic structures and underlying health conditions. Income disparity remains, instead, an important cause of vaccine inequity, and the tendency toward "vaccine nationalism" and "vaccine apartheid" restricts the functioning of the global vaccine allocation framework and, thus, the ending of the pandemic. Stronger mechanisms are needed to foster countries' political willingness to promote vaccine and drug access equity in a globalized society, where future pandemics and other global health rises can be anticipated.

References

[1] Hu, B., Guo, H., Zhou, P. *et al.* Characteristics of SARS-CoV-2 and COVID-19. *Nat Rev Microbiol* **19,** 141–154 (2021). https://doi.org/10.1038/s41579-020-00459-7

[2] Mohapatra, RK, Pintilie, L, Kandi, V, et al. The recent challenges of highly contagious COVID-19, causing respiratory infections: Symptoms, diagnosis, transmission, possible vaccines, animal models, and immunotherapy. *Chem Biol Drug Des*. 2020; 96: 1187– 1208. https://doi.org/10.1111/cbdd.13761

[3] Duhon, J., Bragazzi, N., & Kong, J. D. (2021). The impact of non-pharmaceutical interventions, demographic, social, and climatic factors on the initial growth rate of COVID-19: A cross-country study. *Science of The Total Environment*, *760*, 144325. https://doi.org/10.1016/J.SCITOTENV.2020.144325

[4] Forni, G., Mantovani, A. & on behalf of the COVID-19 Commission of Accademia Nazionale dei Lincei, Rome. COVID-19 vaccines: where we stand and challenges ahead. *Cell Death Differ* **28,** 626–639 (2021). https://doi.org/10.1038/s41418-020-00720-9

[5] Watad, A., De Marco, G., Mahajna, H., Druyan, A., Eltity, M., Hijazi, N., Haddad, A., et al. (2021). Immune-Mediated Disease Flares or New-Onset Disease in 27 Subjects Following mRNA/DNA SARS-CoV-2 Vaccination. *Vaccines*, *9*(5), 435. MDPI AG. Retrieved from http://dx.doi.org/10.3390/vaccines9050435

[6] Rosselli, R., Martini, M., & Bragazzi, N. L. (2016). The old and the new: vaccine hesitancy in the era of the Web 2.0. Challenges and opportunities. *Journal of preventive medicine and hygiene*, *57*(1), E47–E50.

[7] Kricorian, K., Civen, R., & Equils, O. (2021). COVID-19 vaccine hesitancy: misinformation and perceptions of vaccine safety. *Human Vaccines & Immunotherapeutics*, 1–8. https://doi.org/10.1080/21645515.2021.1950504

[8] Tram, K. H., Saeed, S., Bradley, C., Fox, B., Eshun-Wilson, I., Mody, A., & Geng, E. (2021). Deliberation, Dissent, and Distrust: Understanding Distinct Drivers of Coronavirus Disease 2019 Vaccine Hesitancy in the United States. *Clinical Infectious Diseases*. https://doi.org/10.1093/cid/ciab633

[9] Truong, J., Bakshi, S., Wasim, A., Ahmad, M., & Majid, U. (2021). What factors promote vaccine hesitancy or acceptance during pandemics? A systematic review and thematic analysis. *Health Promotion International*. https://doi.org/10.1093/heapro/daab105

[10] Xu, Y., Li, J.-P., Chu, C.-C., & Dinca, G. (2021). Impact of COVID-19 on transportation and logistics: a case of China. *Http://Www.Tandfonline.Com/Action/AuthorSubmission?JournalCode=rero20&page=instructions*. https://doi.org/10.1080/1331677X.2021.1947339

[11] Wagner, C. E., Saad-Roy, C. M., Morris, S. E., Baker, R. E., Mina, M. J., Farrar, J., Holmes, E. C., Pybus, O. G., Graham, A. L., Emanuel, E. J., Levin, S. A., Metcalf, C. J. E., & Grenfell, B. T. (2021). Vaccine nationalism and the dynamics and control of SARS-CoV-2. *MedRxiv*, 2021.06.02.21258229. https://doi.org/10.1101/2021.06.02.21258229

[12] Tagoe, E. T., Sheikh, N., Morton, A., Nonvignon, J., Sarker, A. R., Williams, L., & Megiddo, I. (2021). COVID-19 Vaccination in Lower-Middle Income Countries: National Stakeholder Views on Challenges, Barriers, and Potential Solutions. *Frontiers in Public Health*, *9*, 1145. https://www.frontiersin.org/article/10.3389/fpubh.2021.709127

[13] Hannah Ritchie, Esteban Ortiz-Ospina, Diana Beltekian, Edouard Mathieu, Joe Hasell, Bobbie Macdonald, Charlie Giattino, Cameron Appel, Lucas Rodés-Guirao and Max Roser (2020) - "Coronavirus Pandemic (COVID-19)". Published online at OurWorldInData.org. Available: https://ourworldindata.org/coronavirus

[14] Max Roser (2014) - "Human Development Index (HDI)". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/human-development-index' [Online Resource]

[15] Wang, J., Jing, R., Lai, X., Zhang, H., Lyu, Y., Knoll, M. D., & Fang, H. (2020). Acceptance of COVID-19 Vaccination during the COVID-19 Pandemic in China. *Vaccines 2020, Vol. 8, Page 482*, *8*(3), 482. https://doi.org/10.3390/VACCINES8030482

[16] Tugwell, P., Robinson, V., & Morris, E.B. (2007). Mapping global health inequalities: challenges and opportunities.

[17] The World Bank. World Development Indicators. 2017. Available: https://databank.worldbank.org/source/world-development-indicators

[18] United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019, Online Edition. Rev. 1. Available: https://population.un.org/wpp/Download/Standard/Population/

[19] Geneva, World Health Organization. Global Health Estimates 2015: Deaths by Cause, Age, Sex, by Country and by Region, 2000–2015. 2016. Available: https://www.who.int/healthinfo/global_burden_disease/estimates_regional_2000_2015/en/

[20] Central Intelligence Agency. GINI Index. In: The World Factbook [Internet]. 2017. Available: https://www.cia.gov/library/publications/the-world-factbook/rankorder/2172rank.html.

[21] The World Bank. World Development Indicators. 2019. Available: https://databank.worldbank.org/source/world-development-indicators.

[22] Nuclear Threat Initiative, Johns Hopkins Center for Health Security, The Economist Intelligence Unit. GHS Index. 2019. Available: https://www.ghsindex.org/.

[23] V-Dem Institute. V-dem (version 10). 2020. Available: https://www.v-dem.net/.

[24] Max Roser, Esteban Ortiz-Ospina and Hannah Ritchie (2013) - "Life Expectancy". Published online at OurWorldInData.org. Retrieved from: https://ourworldindata.org/life-expectancy [Online Resource]

[25] Thomas Hale, Noam Angrist, Rafael Goldszmidt, Beatriz Kira, Anna Petherick, Toby Phillips, Samuel Webster, Emily Cameron-Blake, Laura Hallas, Saptarshi Majumdar, and Helen Tatlow. (2021). "A global panel database of pandemic policies (Oxford COVID-19 Government Response Tracker)." Nature Human Behaviour. https://doi.org/10.1038/s41562-021-01079-8

[26] COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University. Available: https://coronavirus.jhu.edu/

[27] United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, Online Edition. Available: https://population.un.org/wup/Download/

[28] World Bank staff estimates based on age/sex distributions of United Nations Population Division's World Population Prospects: 2017 Revision

[29] World Health Organization Global Health Expenditure database. Available: http://apps.who.int/nha/database

[30] Scheil-Adlung, Xenia (2014), Universal Health Protection: Progress to Date and the Way Forward, International Labour Organization. OECD.Stat. Available: https://www.ilo.org/wcmsp5/groups/public/---ed_protect/---soc_sec/documents/publication/wcms_305947.pdf

[31] Global Burden of Disease Collaborative Network. Global Burden of Disease Study 2017 (GBD 2017) Results. Seattle, United States: Institute for Health Metrics and Evaluation (IHME), 2018. Available: http://ghdx.healthdata.org/record/ihme-data/gbd-2017-burden-risk-1990-2017

[32] Phelps, G., & Crabtree, S. (2013, December 16). *Worldwide, median household income about $10,000*. Gallup.com. https://news.gallup.com/poll/166211/worldwide-median-household-income-000.aspx.

[33] International Labour Organization, ILOSTAT database. Available: https://ilostat.ilo.org/data/

[34] UNESCO Institute for Statistics. Available: http://data.uis.unesco.org/

[35] World Health Organization. World report on disability. Geneva: World Health Organization; 2011. Available: https://www.who.int/disabilities/world_report/2011/report.pdf

[36] Ali, J., Khan, R., Ahmad, N., & Maqsood, I. (2012). Random Forests and Decision Trees. *International Journal of Computer Science Issues(IJCSI),* 9(5); 2012. p. 272-278.

[37] Hastie, T., Tibshirani, R., & Friedman, J. (2009). *Springer Series in Statistics The Elements of Statistical Learning Data Mining, Inference, and Prediction*.

[38] Breiman, L. (2001). Random Forests. *Machine Learning*, *45*(1), 5–32. https://doi.org/10.1023/A:1010933404324

[39] Stevenson, A. (2021, May 20). *Countries are scrambling for Vaccines. Mongolia has plenty.* The New York Times. https://www.nytimes.com/2021/05/20/business/coronavirus-vaccine-mongolia.html.

[40] Cendrowicz, L. (2021, August 4). *How Mongolia's COVID vaccination DRIVE surged ahead of West despite poverty and remoteness*. inews.co.uk. https://inews.co.uk/news/world/mongolia-covid-vaccination-drive-how-vaccine-rate-ahead-west-population-1134181.

[41] Lkhaajav, B. (2021, May 6). *How mongolia made the most of vaccine diplomacy*. – The Diplomat. https://thediplomat.com/2021/05/how-mongolia-made-the-most-of-vaccine-diplomacy/.

[42] Duan, Y., Shi, J., Wang, Z., Zhou, S., Jin, Y., & Zheng, Z.-J. (2021). Disparities in COVID-19 Vaccination among Low-, Middle-, and High-Income Countries: The Mediating Role of Vaccination Policy. *Vaccines*, *9*(8), 905. MDPI AG. Retrieved from http://dx.doi.org/10.3390/vaccines9080905

[43] Roghani, A., & Panahi, S. (2021). The global distribution of COVID-19 vaccine: The role of macro-socioeconomics measures. *MedRxiv*, 2021.02.09.21251436. https://doi.org/10.1101/2021.02.09.21251436

[44] Wikipedia contributors. (2021, August 23). Developed country. In *Wikipedia, The Free Encyclopedia*. Retrieved 00:52, August 29, 2021, from https://en.wikipedia.org/w/index.php?title=Developed_country&oldid=1040317801

[45] Ghebreyesus TA. I run the WHO and i know that rich countries must make a choice [Internet]. The New York Times, 2021. Available: https://www.nytimes.com/2021/04/22/opinion/who-covid-vaccines.html [Accessed 31 May 2021].

[46] KFF. Global COVID-19 vaccine access: a snapshot of inequality [Internet], 2021. Available: https://www.kff.org/policy-watch/globalcovid-19-vaccine-access-snapshot-of-inequality/ [Accessed 31 May 2021].

[47] The Economist. More than 85 poor countries will not have widespread access to coronavirus vaccines before 2023 -Economist Intelligence Unit [Internet], 2021. Available: https://www.eiu.com/n/85-poor-countries-will-not-have-access-to-coronavirusvaccines/ [Accessed 31 May 2021].

[48] Nhamo, G., Chikodzi, D., Kunene, H. P., & Mashula, N. (2021). COVID-19 vaccines and treatments nationalism: Challenges for low-income countries and the attainment of the SDGs. *Global public health*, *16*(3), 319–339. https://doi.org/10.1080/17441692.2020.1860249

[49] Tatar, M., Shoorekchali, J. M., Faraji, M. R., & Wilson, F. A. (2021). International COVID-19 vaccine inequality amid the pandemic: Perpetuating a global crisis?. *Journal of global health*, *11*, 03086. https://doi.org/10.7189/jogh.11.03086

[50] Aryeetey, E., Engebretsen, E., Gornitzka, Å., Maassen, P., & Stølen, S. (2021). A step backwards in the fight against global vaccine inequities. The Lancet, 397(10268), 23–24. https://doi.org/10.1016/s0140-6736(20)32596-4

[51] Assessing Country Readiness for COVID-19 Vaccines: First Insights from the Assessment Rollout (English). Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/467291615997445437/Assessing-Country-Readiness-for-COVID-19-Vaccines-First-Insights-from-the-Assessment-Rollout

[52] Veugelers, R. and G. Zachmann (2020) 'Racing against COVID-19: a vaccines strategy for Europe', Policy Contribution 07/2020, Bruegel

[53] Bollyky, T. J., Gostin, L. O., & Hamburg, M. A. (2020). The Equitable Distribution of COVID-19 Therapeutics and Vaccines. *JAMA*, *323*(24), 2462–2463. https://doi.org/10.1001/jama.2020.6641

[54] Fidler, D. P. (2010). Negotiating Equitable Access to Influenza Vaccines: Global Health Diplomacy and the Controversies Surrounding Avian Influenza H5N1 and Pandemic Influenza H1N1. *PLoS Medicine*, *7*(5), e1000247. https://doi.org/10.1371/journal.pmed.1000247

[55] Turner M. (2016). Vaccine procurement during an influenza pandemic and the role of Advance Purchase Agreements: Lessons from 2009-H1N1. *Global public health*, *11*(3), 322–335. https://doi.org/10.1080/17441692.2015.1043743

[56] Ho, A., & Dascalu, I. (2020). Global Disparity and Solidarity in a Pandemic. *Hastings Center Report*, *50*(3), 65–67. https://doi.org/https://doi.org/10.1002/hast.1138

[57] Enserink, G. (2009). The challenge of getting swine flu vaccine to poor nations. *Science*. Retrieved July 23, 2020, from https://www.sciencemag.org/news/2009/11/challenge-getting-swine-flu-vaccine-poor-nations

[58] Saha, S., Tanmoy, A. M., Tanni, A. A., Goswami, S., Sium, S. M. al, Saha, S., Islam, S., Hooda, Y., Malaker, A. R., Anik, A. M., Haq, M. S., Jabin, T., Hossain, M. M., Tabassum, N., Rahman, H., Hossain, M. J., Islam, M. S., & Saha, S. K. (2021). New waves, new variants, old inequity: a continuing COVID-19 crisis. *BMJ Global Health*, *6*(8). https://doi.org/10.1136/bmjgh-2021-007031

[59] COVAX: Working for Global Equitable Access to COVID-19 Vaccines. Available online: https://www.who.int/initiatives/actaccelerator/covax (accessed on 10 June 2021).

[60] WHO. COVAX announces new agreement, plans for first deliveries. https://www.who.int/news/item/22-01-2021-covax-announces-new-agreement-plans-for-first-deliveries (2021).

[61] Burki T. (2021). Global COVID-19 vaccine inequity. *The Lancet. Infectious diseases*, *21*(7), 922–923. https://doi.org/10.1016/S1473-3099(21)00344-3

[62] John TJ. Will coronavirus pandemic eventually evolve as pan-endemic? Current Science. 2020;118:855-56.

[63] Kissler, S. M., Tedijanto, C., Goldstein, E., Grad, Y. H., & Lipsitch, M. (2020). Projecting the transmission dynamics of SARS-CoV-2 through the postpandemic period. *Science*, *368*(6493), 860. https://doi.org/10.1126/science.abb5793

[64] Acharya, K. P., Ghimire, T. R., & Subramanya, S. H. (2021). Access to and equitable distribution of COVID-19 vaccine in low-income countries. *Npj Vaccines*, *6*(1), 54. https://doi.org/10.1038/s41541-021-00323-6

[65] Lee, Y. N. (2021, August 6). *3 charts show how far COVID delta variant has spread around the world*. CNBC. https://www.cnbc.com/2021/08/06/covid-charts-show-how-far-delta-variant-has-spread-around-the-world.html.

[66] Harman, S., Erfani, P., Goronga, T., Hickel, J., Morse, M., & Richardson, E. (2021). Global vaccine equity demands reparative justice — not charity. *BMJ Global Health*, *6*, e006504. https://doi.org/10.1136/bmjgh-2021-006504