UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Inclusive and Sustainable Industrial Development Working Paper Series
WP 7 | 2021

# Collaboration as a determinant of readiness for and progress towards developing a COVID-19 vaccine: a national technological capability approach

DEPARTMENT OF POLICY, RESEARCH AND STATISTICS

WORKING PAPER 7/2021

# Collaboration as a determinant of readiness for and progress towards developing a COVID-19 vaccine: a national technological capability approach

Jahan Ara Peerally
International Business Department
HEC Montreal

Claudia De Fuentes
Sobey School of Business
Saint Mary's University

Fernando Santiago
UNIDO

Julia Paranhos
Instituto de Economia
Universidade Federal do Rio de Janeiro

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna, 2021

## Abstract

Using the World Health Organization's database of candidate vaccines and other secondary data sources, we created a country-level database of (i) the types of collaborations and country-level determinants of technological capabilities for developing a COVID-19 vaccine, and (ii) a measure of countries' readiness for and progress towards developing a COVID-19 vaccine. We examine the effects of these collaborations and determinants on countries with distinct levels of readiness and progress. Private-private collaborations have a strong impact in countries with low levels of readiness and progress, while public-public collaborations are negatively significant. The resilience of public organizations in countries with low levels of readiness and progress needs to be strengthened against major future health challenges. Countries with high levels of readiness and progress have a long-established pool of R&D capabilities and collaborations with domestic and foreign biopharmaceutical organizations. They have the advantage of being able to dip into this pool to rapidly develop a viable and marketable COVID-19 vaccine.

**Keywords:** COVID-19; vaccine; technological capabilities; biopharmaceutical industry; public-public collaborations; private-private collaborations; private-public collaborations; local collaborations; global collaborations; capability building; innovation systems; industrial policy
**JEL Codes:** O14, O32, O57, I15

## Table of Contents



## List of Tables



## List of Figures

## 1. Introduction

Efforts in science, technology and innovation have underpinned the responses to and management of the global COVID-19 health emergency. These efforts have been key in assisting national authorities to secure a steady supply of food, medicines and other COVID-19-related essentials. Both the media and scholars argue that collaborative approaches are the driving force of efforts to contain the pandemic. Efforts to foster academia-industry collaboration as the basis for innovation have yielded alternative solutions to address COVID-19 supply shortages, to minimize the impacts on global supply chains or to tailor solutions to local contexts (BID, 2020). Moreover, advances in scientific and technological knowledge, building on the active collaboration of multiple actors at different levels, have facilitated the development of several candidate COVID-19 vaccines at unprecedented speeds. To date, Pfizer-BioNTech's COVID-19 vaccine, marketed as Comirnaty, is the first COVID-19 vaccine to have been fully approved by several health and drug regulatory agencies as a prophylactic against the COVID-19 disease across different age groups (European Medicines Agency, 2021; FDA, 2021). Such collaborations have also been key for rolling out the production and distribution of various COVID-19 vaccine candidates across the globe (Druedahl et al., 2021; Forman et al., 2021). The availability of COVID-19 vaccines spurs hope that the way out of the pandemic is within reach, at least in those countries that develop and produce vaccines, or in countries with sufficiently deep pockets, advanced foresight and/or the ability to negotiate and gain rapid access to vaccines.[1]

This paper focuses on 'developer' countries that have joined the race to develop a COVID-19 vaccine. We postulate that their ability to successfully develop a vaccine hinges on the collaboration capabilities of the organizations involved, which we consider an output of the developer countries' overall national technological capabilities. We conceptualize success as vaccines that have reached Phase IV in the clinical trial process, i.e. have reached the vaccine development process' market phase, and approval for emergency use in the fight against the current public health emergency (Office of the Commissioner, 2021). Our research question therefore is: *what types of organizational collaborations determine a country's readiness for and progress towards successfully developing a COVID-19 vaccine?*

To answer this question, we adopt the national technological capability approach (Archibugi and Coco, 2004, 2005; Archibugi et al. 2009; Lall, 1992), according to which country-level capabilities are based on the interplay between incentives, institutions, physical investment, human capital and technological efforts. These factors, in turn, determine the innovative

[1] We acknowledge that availability of vaccines has been insufficient, as both the approval and demand for COVID-19 vaccines determine and constrain their roll out across the world.

capabilities of organizations in developer countries. We contend that organizations' capacity to innovate implies the existence of collaboration capabilities.

The remainder of this paper is structured as follows. Section 2 presents a literature review of types of collaborations for developing biopharmaceutical innovations, industrial policies for building collaboration capabilities in healthcare and biopharmaceuticals and what we presently know about collaborations in the COVID-19 vaccine landscape. Our methodology is outlined in Section 3, and our results are discussed in Section 4. Section 5 concludes with a discussion on the implications of such collaborations and the building of national technological capabilities to address huge health challenges. We also propose future areas of research.

## 2. COVID-19 vaccine development: a collaborative endeavour

### 2.1 Organizational collaborations to develop biopharmaceutical innovations

Innovation is a systemic, non-linear, interactive and socially determined process, which encompasses several sources of knowledge that are necessary to generate it. Firms are considered the locus of innovation, but several studies (Arora and Gambardella, 1994; Frenz and Ietto-Gillies, 2009; Scandura, 2016) demonstrate that firms cannot depend on their internal resources alone to innovate. Knowledge quickly becomes obsolete, forcing firms to continuously seek new and external sources of knowledge to gain competitive advantages through innovations (Arora and Gambardella, 1990).

The biopharmaceutical industry—a science-based sector according to Pavitt's (1984) taxonomy—rests on scientific knowledge, a key ingredient of innovation (Jensen et al. 2007; Parrilli and Heras, 2016), thus necessitating organizational collaboration between different scientific actors. Biopharmaceutical firms are more inclined to developing closer relationships with universities. Triulzi, Pyka and Scholz (2014) find that interactions with universities significantly enhance biopharmaceutical firms' innovation potential, as universities can pursue a wider range of research and possess a more exclusive set of know-how (Rosenberg and Nelson, 1994). Hence, collaboration with universities is crucial for expanding scientific knowledge and generating new discoveries, but also to have access to and to be able to utilize valuable resources, such as renowned scientists and advanced research facilities (Subramanian, Lim and Soh, 2013).

When academic research is translated into commercial applications, firms apply both explicit and tacit components of new knowledge, which are often interdisciplinary and complex (Arora and Gambardella, 1994). Relationships with universities increase firms' pool of human resources—a pool that already possesses the practical knowledge to work in the given industry—with additional technical and scientific knowledge. That is, knowledge exchange between the industrial and

academic sectors is an essential mechanism for bringing science to the market and for promoting innovation and economic growth (OECD, 2002; Perkmann et al., 2021).

The development of innovations in the biopharmaceutical industry is a lengthy process that consists of several phases – from identifying a molecule to the pre-clinical phase, which involves toxicology and security studies on animals, to Phases I to IV involving clinical trials in humans. A controlled number of volunteers participates in Phases I to III, a mandatory prerequisite when applying for commercialization approval from the appropriate regulatory agencies. Marketing approval is gained in Phase IV once safety and efficiency under conditions of normal use have been proven (Abecassis and Coutinet, 2008).

This process is long, costly, uncertain and complex. Stringent regulatory standards must be met not only in research, but also in production and commercialization. The increasing regulatory requirements since the 1990s have intensified change in the vertical movement of research and development (R&D) phases in the biopharmaceutical industry, giving rise to a new set of collaborators, namely contract research organizations in R&D outsourcing (Abecassis and Coutinet, 2008). Moreover, the emergence of biotechnology has increased the complexity and requirement to master different types of knowledge for drug development (Malerba and Orsenigo, 2015). These changes continue to expand the need for collaborations in the development of new drugs.

Regardless of these changes, biopharmaceutical firms' internal R&D activities remain crucial to their own operations, enabling accumulation of the necessary capabilities to absorb new knowledge, i.e. absorptive capacity, generated through interactions with other collaborators (Cohen and Levinthal, 1990). In fact, it has been demonstrated that firms that are capable of establishing a balance between internal R&D investment and external collaborations are more innovative (Arora and Gambardella, 1990; Bercovitz and Feldman, 2007; Gilsing and Nooteboom, 2006; Hess and Rothaermel, 2011).

Biopharmaceutical firms that conduct joint R&D activities with universities expand their existing knowledge application, which results from several technological controls during the development of patented technologies (Soh and Subramanian, 2014). Such partnerships can stimulate other types of collaboration as well, since universities improve firms' technological opportunities and strategies to cooperate in R&D (Belderbos et al., 2004).

The internationalization of R&D collaboration in the biopharmaceutical industry is important for gaining access to foreign and often more advanced knowledge to improve one's own competitiveness. International collaborations have increased since 2006 (Hu, Scherngell, Qiu and

Wang, 2015), evolving from a monocentric network spearheaded by the United States (henceforth U.S.) to a more dispersed and denser network consisting of a wider distribution of R&D collaborations between a larger number of countries, particularly European countries. Hu et al. (2015) show that the U.S.' relative dominance—from a network perspective—has decreased over time, while intra-European R&D collaborations have intensified; collaborations with, and among developing countries have remained static.

Such shifts in the structure of networks denote a shift in the type and intensity of collaborations which often hinge on countries' history, institutions, stage of development and degree of knowledge accumulated within their organizations (Faulkner and Senker, 1994). Developed countries can look back on a long history of collaboration between academic researchers and the industrial sector, while the fragile and unstable institutions in developing countries have acted as a barrier for such interactions (Santiago and Dutrénit, 2012).

Bignami, Mattsson and Hoekman (2019) suggest that biopharmaceutical firms tend to favour local R&D collaboration networks to develop radical, highly tacit, state-of-the-art drug innovations. Close partnerships allow organizations to respond quickly to emerging innovation opportunities and to hire highly skilled professionals. Clinical trials, on the other hand, tend to involve global partners, because the regulatory phases of drug development must be meticulously documented across borders. As codified knowledge is more easily transferrable, the same protocol can be applied in different sites despite geographical distance. Moreover, a broad and multiracial cohort of volunteers from different countries is important for testing a drug's efficacy and side effects (Bignami et al., 2019). Likewise, tests involving the local population are important for securing access to prospective markets (Santiago, 2010).

Belderbos et al. (2021) emphasize the important role decentralized biopharmaceutical R&D units play in leading global collaborations, particularly for firms' core knowledge areas. They analyse foreign university collaborations in the biopharmaceutical industry and find that despite a generally increasing presence of local decentralized R&D units of biopharmaceutical firms in foreign countries, the share of foreign university collaborations with local units decreases over time. Belderbos et al. argue that while there are still advantages to collaborating through decentralized local units in case of non-spatial and geographic distance between a firm's central R&D unit and a local university, these advantages might be outweighed by considerations of creating, transferring, recombining and appropriating knowledge resources. Their findings thus indicate that firms do not only consider factors related to the organization of R&D, but also weigh the decision on how to conduct R&D with foreign universities from a strategic and competitive perspective. They conclude that the amount of knowledge and expertise accumulated by the firm

in a given research area and the risk of that knowledge leaking to competitors in the vicinity of the foreign university, is a key concern when deciding what types of R&D collaborations to pursue in foreign locations.

## 2.2 Industrial policies for building collaboration capabilities in healthcare and biopharmaceuticals

Mackintosh et al. (2016) explore a field of research that emerged in the 1990s, which perceives healthcare and healthcare policies as 'implicit'[2] industrial policies. Healthcare generates relevant demand and investment incentives for the development of medicines, medical supplies and other related products and services. It is equally important to note that the significant contributions made by scholars from developing countries, notably from India and Brazil (Mackintosh et al. 2016) with an emphasis on market environments and the development of a 'health-industry complex'[3], frame issues of access and the right to health. Mackintosh et al. (2018) highlight the importance of coordinating industrial, science and health policies as part of a strategy to secure biopharmaceutical supplies for local healthcare. They assert that these three policy domains—industry, science and health—directly connect risk management with local health security, safety and responsibility, which translates into efforts to mitigate risks by building greater technical and organizational capabilities in health- and industry-related skills. They (2018:603) also introduce the notions of 'proximity'—understood as the "cumulative local interactions and mutual influences arising from co-location"—and 'positionality'—or "the influence of location of agency on the framing of issues and priorities, with attendant claims to power and legitimacy in policy making"—to illustrate the interconnections of local health policy and the accumulation of local capabilities to promote industrial change.

Building on the experiences of Kenya and Tanzania, Mackintosh et al. (2016) and Mackintosh et al. (2018) propose several incentives to build 'collaborative capabilities'[4] that underpin mutually reinforcing responsiveness and synergies between the health and industrial systems – each system benefits from the opportunities offered by the other. Such incentives can leverage the health sector's huge market potential to capture the demand for affordable, quality and safe products with different degrees of technological complexity, and to benefit from training and skills development requirements, which has the potential of sustaining technological upgrade in manufacturing. Conversely, boosting domestic industrial capacities could contribute to addressing pressing healthcare needs. Mackintosh et al.'s (2016) emphasis on co-location, shifting

[2] Emphasis in original by the author.
[3] Emphasis in original by the author.
[4] Emphasis in original by the author.

local market structures, regulation and demand patterns as drivers of synergies between healthcare and manufacturing is reminiscent of the findings of Lee and Malerba's (2017) innovation studies, according to which market identification, regulation and demand present windows of opportunities for catching up and forging ahead.

Srinivas' (2015) account of the development of the *Haemophilus influenzae* type B (Hib) vaccine is consistent with Mackintosh et al.'s (2016:164) claim that coherence between health and industrial policies is a social construction that must be "built over time through institutional generation of collaborative capabilities in both sectors, and associated incentives for extracting mutual benefit". Srinivas (2015) describes vaccines as outcome pathways to innovation, i.e. they are "developed within significant financial, material or institutional constraints"[5], but may include 'high-tech'[6] innovations. This is illustrated by the case of the Hib vaccine that was developed in Cuba. It is important to note that such innovations draw on scarce resources and are adapted to local contexts. The Hib example is of particular relevance here because it entailed close collaboration between Cuban and Canadian researchers on a vaccine that was a priority for the Cuban healthcare system, a challenging undertaking considering the conventional means of importing expensive drugs. The development of a more affordable Hib vaccine was a scientific and public health revolution according to Srinivas, as significant efforts were necessary on the part of both research and public support and financing to scale up and manufacture homegrown alternatives, with an emphasis on addressing a human need and deliberately side-lining the focus on profit. The development of the new Hib vaccine can therefore also be described as a problem-solving endeavour (Srinivas, 2015). This view is also reflected in Mackintosh et al.'s (2016) findings on the need for incentives to build 'collaborative capabilities' and their conclusion that the legitimacy of problem-solving innovations rests on agile institutions with employees and rules that are both flexible and oriented towards timely outcomes. They assert that outcome measures must be clear and transparent; they must also be monitored and properly enforced. Such collaborative efforts between public health research institutes, a network of clinics and outreach mechanisms linked directly to families and children, which facilitated the development of a vaccine, eventually contributed to curbing mortality and morbidity from paediatric meningitis in developing countries.

[5] https://sowc2015.unicef.org/stories/pathways-less-traveled-including-children-in-overcoming-scarcity/
[6] Emphasis in original by the author.

## 2.3 Collaborations in the COVID-19 vaccine landscape

Two types of collaborations characterize the COVID-19 vaccine landscape and efforts to get a handle on the pandemic. The first type comprise cross-border collaborations between states and supranational/international organizations to fund and/or support vaccine development, production and equitable distribution efforts. This includes, for example, the COVID-19 Vaccine Global Access Facility (COVAX), which was established by the World Health Organization (WHO), the Coalition for Epidemic Preparedness Innovations (CEPI) and the Vaccine Alliance (GAVI), a Swiss-based public-private partnership for vaccine supply and procurement. COVAX, a global collaboration, involves procurement agreements that reserve vaccine doses for populations in both developing and developed countries. This collaboration functions not only as a global procurement mechanism, but also as a resource-pooling, risk-sharing and push financing mechanism and could become the largest vaccine procurement scheme in history (Brasnwell, 2020; WHO, 2020).

The second type of collaborations involve domestic and foreign organizations working together to develop COVID-19 vaccines. This paper focuses on this second type of collaborations. At the time of writing, at least seven different vaccines had already reached the market stage and were being administered around the world, while over 200 additional vaccine candidates were being developed, over 60 of which had already entered the clinical development phase. It took less than a year to roll out a number of vaccines across three different platforms, and over 7.35 billion doses have been administered in more than 130 countries (Nature, 2021a; Bloomberg, 2021). Despite these major achievements, significant challenges in vaccine development remain. Forman et al. (2021) note that there still is insufficient knowledge on whether the currently administered vaccines will remain effective in the long run; whether emerging variants might carry a large number of mutations with high vaccine escape potential; or whether annual or periodic boosters might become necessary. Although they (2021:565) describe the vaccines that have emerged in the fight against COVID-19 as “extraordinary developments”, they are only one tool in a shed of available mechanisms to tackle COVID-19. Forman et al. (2021) call for continued long-term efforts to develop new vaccines with the aim of optimizing their safety, effectiveness and quality. They also support continued incentives to maintain robust R&D efforts and to generate second and third generation vaccines to meet the ever-changing needs of populations across the globe. With the emergence of new variants, interest in the development of a universal ‘variant-proof’ vaccine with the ability to fend off different varieties of the same virus family is rising (Ahuja, 2021).

Other studies that use descriptive statistics also shed some light on different types of collaborations to develop a COVID-19 vaccine. Jasso-Villazul and Torres-Vargas (2020), for example, identify and describe the new forms of collaborations between firms, public research institutes, universities and governments that have emerged to accelerate the development of COVID-19 vaccines. Yet collaborations for vaccine development are not new. Archibugi and Bizzarri (2004) and Druedahl et al. (2021), for example, note that such collaborations may involve partnerships between private and public entities, or hybrids such as industry-industry partnerships. Academia-industry partnerships have driven vaccine development and production in the past, supplied developing countries with vaccines and have played a crucial role throughout the COVID-19 crisis (Druedahl et al., 2021).

Two studies focus on scientific research collaborations between countries and organizations to develop COVID-19 vaccines. Radanliev et al. (2020) carried out data mining of scientific literature, for example, to investigate the scientific research response during the early stages of the COVID-19 pandemic. They find that Chinese universities dominated the research efforts on COVD-19-related topics, namely on viruses, pandemics and mortality, in the early days of the pandemic. They also report strong collaborations on COVID-19 research between the U.S. and China. Their analysis of research on the COVID-19 vaccine specifically reveals that even though the U.S. leads in terms of volume of scientific research, the three leading research institutes are located outside the U.S., namely in China, Australia and the United Kingdom. It was therefore difficult to predict which country would produce a COVID-19 vaccine first.

Wang and Hong (2020) reviewed a total of 27,370 COVID-19-related articles published between 1 January and 1 July 2020. The U.S. was the most active and productive country in COVID-19 research, with the largest number of publications and collaborations. Huazhong University of Science and Technology in China was the most productive in terms of number of publications, and the University of Toronto in Canada ranked first in global research collaborations. The U.S. and China were the two most productive countries overall, but pursued very different approaches. Because the initial outbreak of COVID-19 occurred in China, Chinese scholars rapidly carried out a series of studies and published numerous articles in the early stages of the epidemic (Wang and Hong, 2020). Chinese scholars tended to collaborate with domestic rather than with foreign scholars. A significant increase in the number of publications was observed in the U.S. from April 2020 onwards, matched by the highest level of participation in global collaborations due its scientific research strengths and influence. Wang and Hong also note that inter-organizational collaboration tended to be mostly domestic in nature both in China and the U.S.

## 2.4 Insights from the literature review

We can infer that advanced research on radical or state-of-the-art innovations is conducted locally by centralized R&D units of organizations or by units close to the organization's headquarters. Clinical trials, which play a fundamental role in the development of new drugs, are more codified and can be conducted by foreign R&D units under the coordination of their headquarters. Bignami et al. (2019) find that distance and willingness to invest are important factors in biopharmaceutical firms' decision to collaborate when the potential collaboration relates to the firm's core knowledge areas rather than to new or peripheral ones. This implies that biopharmaceutical firms search for knowledge that is most relevant to their core activities, regardless of the collaborator's location. Hence, the question whether biopharmaceutical organizations engage in local or global collaborations to develop major innovations remains ambiguous.

In line with Forman et al.'s study (2021), we reckon that further research is necessary to optimize the COVID-19 vaccine. Under this premise, we argue that insights into the types of collaborations that have given rise to the currently available COVID-19 vaccines continue to be a priority as we move forward with the pandemic. There is therefore a genuine need to continue investigating what types of collaborations are compatible with a country's readiness for and progress to successfully develop COVID-19 vaccines.

We also reckon that collaborations for vaccine development are not new, and involve partnerships in and between industry, academia (university and research institutes) and academia-industry collaborations. Indeed, the WHO, CEPI, and European Commission assert that global collaborations between key stakeholders—political leaders, the public sector, industry, civil society and academia—play a central role in efforts to accelerate the development, production and equitable access to new COVID-19 diagnostics, therapeutics and vaccines (CEPI, 2021; European Commission, 2021; WHO 2021). Our study takes an in-depth look at the relevance of these different types of collaborations at the country level in the race to develop COVID-19 vaccines.

Finally, while Radanliev et al. (2020) and Wang and Hong (2020) provide insights into the contributions of both the U.S. and China as leaders in scientific research on COVID-19-related issues, Nature (2021b) reports that cross-country collaborations have been waning, especially in China and the U.S., and that Chinese collaborations with the U.S., for example, have been decreasing since 2017.

In short, several theories on the role of collaborations to develop COVID-19 vaccines exist. We attempt to disentangle this plethora of theories by exploring how different countries have engaged

in various types of collaborations in and between industry, academia and university-industry partnerships, and what role they play in terms of a country's readiness for and progress towards successfully developing COVID-19 vaccines. Our results shed further light on the implications of country-level technological capabilities and collaborations between organizations for the successful development of COVID-19 vaccines.

# 3 Methodology

## 3.1 Data collection

To explore the relationship between countries' readiness for and progress towards developing COVID-19 vaccines and their national technological capabilities—including collaborations—we collected data at the level of vaccine development and of organizations involved, as well as proxy indicators for national technological capabilities in line with Archibugi and Coco (2004, 2005) and Lall (1992). We also collected data on different types of collaborations involving public organizations, universities and industry, and classified them according to local or global collaboration for each vaccine at every stage of development. We then created two databases, one at the firm level and the other at the country level. Data on the vaccine- and organization level and on collaborations were merged in the latter database.

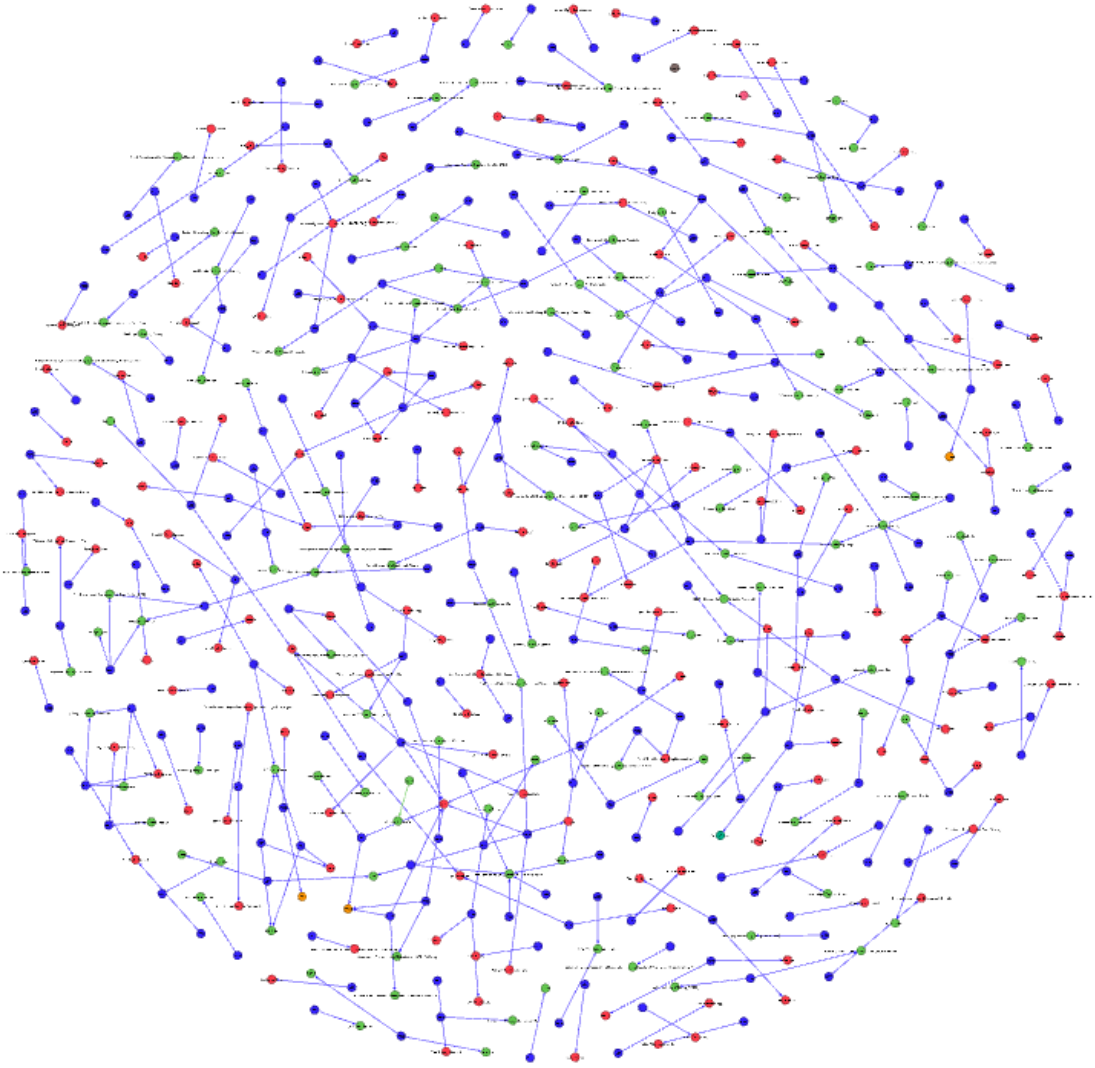
We used the WHO's 'COVID-19 landscape of novel coronavirus candidate vaccine development worldwide database' released on 5 March 2021 (which is also the cut-off date for our analysis) to create our firm-level database. It includes 259 COVID-19 vaccines of which 255 were in different phases—from the pre-clinical stage to Phase III (clinical trial stage)—and four were in Phase IV, i.e. in the market stage, and were being licensed and rolled out across the globe. The WHO database includes information on the organizations involved in vaccine development as well as other information such as the technological platforms used to develop the vaccines (e.g. protein subunit, inactivated virus), the number of doses required, and the route of administration (e.g. oral or injectable). Our firm-level database identifies the country of origin of each of the organizations involved in the development of the 259 vaccines, as well as their status in terms of ownership or their role in the development of the vaccine. To identify country of origin, we used internet searches to determine the location of the organization's headquarters. In case of multinational or international organizations, we used the location of their headquarters to indicate their country of origin based on the premise that the organization's home country usually is credited with vaccine development. The 259 vaccines included in our study had been or were being developed by a total of 229 organizations and 40 different developer countries. Some of the 229 organizations participated in several vaccine development projects across different countries.

As regards the status of the organizations in terms of ownership or their role in vaccine development, those that were not state-owned or -funded were listed as 'private' and included enterprises, private non-profit organizations and private foundations. All state-owned or -funded organizations/enterprises were labelled as 'public'. Universities include both private and public universities; we labelled them as 'universities' due to their distinct role in knowledge creation within modern industrial innovation systems (Lall, 1992; Mowery and Sampat, 2005; Nelson, 1992). Teaching hospitals and laboratories within universities were also coded as 'universities'. We retrieved these data from the internet through desk-based research.

Figure 1 presents the network of public (green nodes), private (red nodes) and international organizations (orange nodes) involved in the development of 259 COVID-19 vaccines (blue nodes). We observe that collaborations between public-public organizations, private-private organizations and public-private organizations have been essential in the development of COVID-19 vaccines. We also find that the same organizations collaborate or collaborated in the development of more than one vaccine at different stages of development.

Table 1 below shows the different types of collaborations and the geography of collaborations (local or global). Table 2 presents the types of vaccine technology developed and indicates whether the vaccines under development are being produced without collaboration, by local collaborations only, or by global collaborations. Most candidate COVID-19 vaccines were developed without collaboration, while the majority of collaborations involved public and private organizations at the local level.

**Figure 1: Network of public, private and international organizations for the development of COVID-19 vaccines**



*Source*: Authors based on the firm-level database.

*Note*: Blue nodes indicate vaccines, red nodes represent private organizations, green nodes are public organizations and orange nodes depict international organizations.

**Table 1: Cross-tabulation of types of collaborations in the development of COVID-19 vaccines**

| | No collaboration | Public-public collaborations | Private-private collaborations | Private-public collaborations |
|---|---|---|---|---|
| No collaboration | 162 | 0 | 0 | 0 |
| Local collaborations | 0 | 14 | 10 | 35 |
| Global collaborations | 2 | 2 | 17 | 17 |
| Total | 162 | 18 | 27 | 52 |

*Source*: Authors based on the firm-level database.

*Note*: The cell representing no collaboration and global collaborations indicates the same organization collaborating in different global settings.

**Table 2: Vaccine technology and local versus global collaborations**

| Vaccine technology | No collaboration | Local collaborations | Global collaborations |
|---|---|---|---|
| Protein subunit | 59 | 22 | 12 |
| Virus like particle | 17 | 3 | 1 |
| RNA based vaccine | 17 | 8 | 4 |
| DNA based vaccine | 14 | 7 | 5 |
| Viral vector (Replicating) | 14 | 4 | 4 |
| Inactivated virus | 13 | 3 | 5 |
| Viral vector (Non-replicating) | 21 | 9 | 4 |
| Live attenuated bacterial vector | 1 | 1 | 0 |
| Cellular based vaccine | 1 | 0 | 0 |
| Viral vector (Non-Replicating) + APC | 1 | 1 | 0 |
| Viral vector (Replicating) + APC | 1 | 0 | 1 |
| Bacterial vector (Replicating) | 1 | 0 | 0 |
| Live attenuated virus | 0 | 1 | 2 |
| Total | 160* | 59* | 38 |

*Source*: Authors based on the firm-level database.

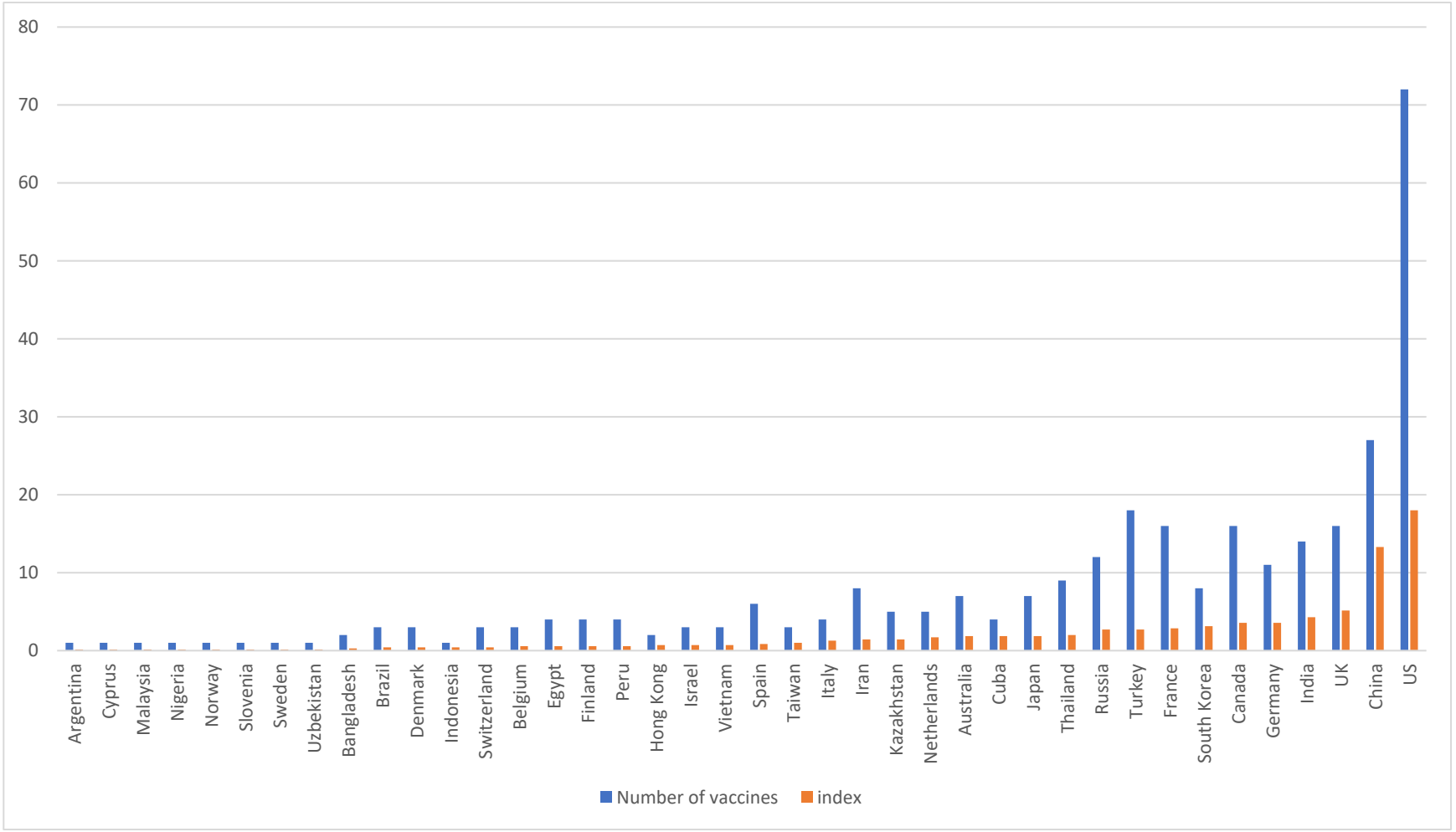
*Note*: *1 missing data, vaccine technology not reported in the original WHO database.

## 3.2. Variables

Building on the above-described firm-level database, we aggregated the data collected at the firm level to create a country-level database with 40 country cases. Since our research question is: *what determines a country's readiness for, and progress towards successfully developing a COVID-19 vaccine?*, we developed an index to measure countries' readiness for and progress in the development of COVID-19 vaccines. This index—our dependent variable—is based on each developer country's total number of vaccines and the vaccines' individual phase (pre-clinical or clinical trials). These data were retrieved from the abovementioned WHO database. The index inherently captures the notion of progress—from the pre-clinical trial stage to Phase IV—of the 259 vaccines. We normalized the index from 0-18; the distribution, i.e. the readiness for and progress of countries towards developing COVID-19 vaccines, is presented in Figure 2. The U.S. and China are visibly in the lead. The distribution of vaccines by country level amounts to 300 vaccines as in some cases, more than one country collaborated on one vaccine. Thus, our country-level database accounts for each collaborating country.

We focus on two main measures to identify the main determinants for countries' readiness for and progress towards developing COVID-19 vaccines. First, we explore the types of collaborations underpinning the development of each vaccine at country level involving different types of organizations within and across national boundaries. Our firm-level database is highly granular and captures all instances of no collaboration, the status of single developers (e.g. private, public, university) and all instances of collaborations between two or more collaborators with varying statuses in terms of ownership or their role in the development of COVID-19 vaccines. At such a granular level, however, we do not have enough cases to run econometric tests. We therefore combined the different types of collaborations in a methodologically and conceptually sound and rigorous way to be able to run econometric tests. For example, collaborations between public-private international organizations, public-private organizations and private-university were combined and recoded as 'public-private collaborations'. Collaborations that involved private-private organizations or private-private international organizations were recoded as 'private-private collaborations'. Collaborations that included public-public, university-university, public-international organizations or public-university were coded as 'public-public collaborations'. In many cases, and as is expected in the development of vaccines, more than two organizations collaborated in the development of COVID-19 vaccines. Thus, public-private-private collaborations were captured as both 'public-private' and 'private-private' collaborations. If the headquarters of an organization involved in the development of a vaccine was located in a different country, we coded that collaboration as a global collaboration; when the collaboration

**Figure 2: Number of vaccines per country and index of country's readiness and progress**




*Source*: Authors based on the country-level database.

involved domestic organizations only, we coded it as a local collaboration. Our main independent variables thus comprise public-private collaborations, private-private collaborations, public-public collaborations and local versus global collaborations.

Second, we also accounted for multi-level determinants, namely country-level indicators for national technological capabilities (Archibugi and Coco, 2004, 2005; Archibugi et al. 2009; Lall, 1992; Zukauskaite et al. 2017). Following Archibugi and Coco (2004, 2005), Archibugi et al. (2009) and Lall, (1992), our country-level control variables for the accumulation of technological capabilities included gross domestic product (GDP) per capita[7] and the Global Innovation Index[8] (GII) which, according to Lall (1992), represent macro-economic incentives for organizations to develop a vaccine. GII is a composite index of countries' institutions, human capital and research, infrastructure, market sophistication, business sophistication, knowledge and technology outputs and creative outputs. Patents in pharmaceuticals[9] are measured as the average number of patents produced by a developer country between 2010 and 2019 (2019 is the latest year of available data). This indicator represents national technological efforts in building technological capabilities (Lall, 1992). A dummy variable was used to indicate whether the developer country is a member of the International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use[10] (ICH). ICH membership is a proxy for the strength of developer countries' organizations in terms of technological capabilities (Lall, 1992). Hence, a country's membership in the ICH reflects its institutional strength and potential for building national technological capabilities. The descriptive statistics of these variables are presented in Table 3 and their correlations are shown in Table 4.

[7] From World Bank Indicators; https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?view=chart.
[8] Retrieved from https://www.wipo.int/global_innovation_index/en/.
[9] From World Intellectual Property Organization; Patent publications by technology: 16 – Pharmaceuticals https://www3.wipo.int/ipstats/editIpsSearchForm.htm?tab=patent.
[10] Retrieved from https://www.ich.org/page/members-observers.

**Table 3: Descriptive statistics**

| Variable | Operationalization | Obs. | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|---|
| Index | Index from 0-18 which indicates each country's number of vaccines in pre-clinical trials or clinical trials Phases I to IV. | 40 | 2.054 | 3.447 | 0.143 | 18.00 |
| Number of vaccines | Continuous variable which indicates the total number of vaccines being developed by each country | 40 | 7.775 | 11.984 | 1.000 | 72.00 |
| Private-public collaborations | Dummy variable which indicates collaboration between private and public organizations | 40 | 1.625 | 2.993 | 0.000 | 16.00 |
| Private-private collaborations | Dummy variable which indicates collaboration between private organizations | 40 | 1.525 | 3.823 | 0.000 | 23.00 |
| Public-public collaborations | Dummy variable which indicates collaboration between public organizations | 40 | 0.625 | 1.427 | 0.000 | 6.00 |
| Global collaborations | Dummy variable which indicates collaboration between local and foreign organizations | 40 | 0.525 | 0.506 | 0.000 | 1.00 |
| Log GDP per capita | Continuous variable which indicates GDP per capita in log form | 40 | 9.755 | 1.173 | 7.453 | 11.314 |
| Patents in pharmaceuticals | Continuous variable which indicates the number of patents in pharmaceuticals | 39 | 2399.395 | 6151.336 | 1.000 | 28537.70 |
| ICH membership | Dummy variable which indicates whether the country is a member of the ICH Council | 40 | 0.425 | 0.501 | 0.000 | 1.00 |
| GII ranking | Continuous variable which indicates the GII rank | 38 | 43.579 | 38.525 | 2.000 | 124.00 |

*Notes*: ICH - International Council for Harmonisation of Technical Requirements for Pharmaceuticals for Human Use; GII - Global Innovation Index.

**Table 4: Correlation table**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Index (1) | 1 | | | | | | | | | |
| Number of vaccines (2) | 0.944 | 1 | | | | | | | | |
| Private-public collaborations (3) | 0.921 | 0.891 | 1 | | | | | | | |
| Private-private collaborations (4) | 0.921 | 0.947 | 0.908 | 1 | | | | | | |
| Public-public collaborations (5) | 0.857 | 0.797 | 0.818 | 0.811 | 1 | | | | | |
| Global collaborations (6) | 0.365 | 0.288 | 0.355 | 0.313 | 0.251 | 1 | | | | |
| Log GDP per capita (7) | 0.149 | 0.179 | 0.236 | 0.202 | 0.147 | 0.305 | 1 | | | |
| Patents in pharmaceuticals (8) | 0.930 | 0.811 | 0.883 | 0.851 | 0.875 | 0.290 | 0.183 | 1 | | |
| ICH membership (9) | 0.348 | 0.339 | 0.266 | 0.209 | 0.166 | 0.062 | 0.026 | 0.313 | 1 | |
| GII ranking (10) | -0.114 | -0.117 | -0.195 | -0.170 | -0.127 | -0.310 | -0.815 | -0.141 | 0.108 | 1 |

We used quantile regressions to analyse our data. We differentiated the quantiles based on the specific index per country. Hence, each quantile denotes three different percentiles of the readiness and progress index (0.25, 0.5 and 0.75). By using quantile regressions, we are able to identify the effect of collaborations and country-level readiness and progress in the specific quantiles of vaccine development per country. Our equation is as follows:

$$qy(\tau) = \alpha + \beta_1 x_{1i} + \beta_2 x_{2i} + u$$
$$\tau \in (0, 1)$$

where:

$y$ is our dependent variable of the readiness and progress index for each country.

$\tau$ represents each quantile and $\tau \in (0, 1)$.

$x_{1i}$ is our matrix of dependent variables as indicated by type of collaboration, and includes 'public-public', 'private-private', and 'public-private' collaborations.

$x_{2i}$ is our matrix of control variables at the country level represented by GDP per capita, the country's GII ranking, patents in pharmaceuticals and ICH membership.

$u$ is the error term.

We ran four different models due to the limited number of available observations, which prevented the inclusion of all control and independent variables into one equation simultaneously[11]. In the following section, we discuss the results of our regression analyses.

## 4. Results and discussion

We implemented a quantile regression analysis because the quantile regression estimator is a nonlinear one (Hilbe et al., 1992) and adds 'transparency' to the results, especially when working with a dependent variable that does not have linear behaviour. The results of the estimation reveal the impact different types of collaborations and country-level indicators of national technological capabilities have on the indicator index for country readiness and progress towards developing COVID-19 vaccines.

[11] It must be noted that we collected data on various determinants of technological capabilities that are relevant for the development of COVID-19 vaccines and that we ran regressions for them, but the results were not significant. Due to the limited number of observations, we report the models for which the determinants are significant. We comprehensively explored determinants including countries' GDP, GDP per capita and GDP growth; science, technology and innovation policies (such as R&D expenditure as a percentage of GDP; total R&D professionals per million inhabitants; number of patent publications in medical technology, biotechnology, and biopharmaceuticals); the effectiveness of industrial institutions (U.S. Chamber International Intellectual Property Index; Global Innovation Index); and health policies (such as child immunization rates and child mortality rate), import and export of vaccines as a percentage of the country's total value of trade, as well as in trade value in dollars per capita and in percentage growth.

We begin our analysis and discussion of the results on the country-level variables and across the four sets of regression models as shown in Table 5. In Models 1 and 2, we control for GDP per capita and the countries' ranking in the GII. These two variables are proxies which represent the macro-economic incentives within developer countries and for their organizations to develop a vaccine. The results suggest that macro-economic incentives are not a significant determinant of a country's readiness for and progress towards developing COVID-19 vaccines.

In Model 3, we control for the average number of pharmaceutical patents issued by the developer countries. This is an indicator of the accumulation of knowledge and innovation capacity in a country's biopharmaceutical organizations. This variable is highly significant for countries with low, medium and high levels of readiness for and progress towards developing COVID-19 vaccines. By combining the results obtained from Models 1 and 2 with the results from Model 3, we deduce that since COVID-19 vaccines were developed very quickly, the organizations within the developer countries largely relied on the existing pool of knowledge within their national innovation systems. Thus, the accumulation of prior knowledge in biopharmaceuticals rather than macro-economic incentives influence the ability to develop a vaccine rapidly and successfully.

In Model 4, we control for countries' membership in the ICH. The results suggest that by adopting the principles of the ICH and consequently by having established both strong regulatory authorities and pharmaceutical industries, countries will also have a high level of readiness for and progress towards the development of COVID-19 vaccines.

In terms of firm-level collaborations, our results across models suggest that private-private collaborations have a strong impact on countries with low levels of readiness for and progress towards developing COVID-19 vaccines. This seems to indicate that the bulk of knowledge for developing a vaccine in these countries resides with private organizations. Public-public collaborations are negatively significant for the same category of developer countries. Thus, our results suggest that if a country with low levels of readiness for and progress towards developing COVID-19 vaccines aims to strengthen its vaccine development capabilities to address major future health challenges, it must strengthen its public organizations as well. Indeed, GAVI (2020) predicts that pandemics such as COVID-19 will become more frequent in the future, therefore, investing in efforts to accumulate and expand the knowledge of different types of organizations is crucial to enable rapid responses to health crises.

Global collaborations are significant in Model 3 only, and for countries with a medium and high level of readiness for and progress towards developing COVID-19 vaccines. These results suggest that countries that have built national technological and R&D capabilities in the biopharmaceutical industry, measured by their average number of patent publications, have a better record of global collaborations with other biopharmaceutical actors within the domestic and in foreign innovation systems. This leads back to our previous argument that the rapid development of a vaccine requires an existing base of accumulated knowledge and technological capabilities, and since developing effective global collaborations takes time, we surmise that what we are capturing here is that lasting collaborations as opposed to creating new ones is of particular relevance in emergency situations. As Steinmo (2015) argues, both cognitive and relational social capital are key for the success of effective collaborations in research partnerships. Our findings also reinforce the notion that organizations embrace a network strategy when engaging in the development of important innovations, as also observed by Hu et al. (2015).

Our results on the national technological capabilities of developer countries suggest that path dependency and the knowledge that is built and accumulated in the field of biopharmaceuticals have an important impact on countries' readiness for and progress towards developing COVID-19 vaccines. This finding reinforces the well-tested notion, as discussed by Archibugi and Coco (2004, 2005), that the accumulation of national technological capabilities is a purposive process and requires deliberate efforts to contribute to the creation of organizational-level knowledge for the development of innovations.

Finally, our results suggest that the main explanatory factors for readiness for and progress towards the development of COVID-19 vaccines as measured by different types of collaborations within and across the 40 developer countries included in our study are the effectiveness and outcomes of the latter's industrial institutions and policies. Thus, organizations' openness to collaborations emerges as the driver of countries' readiness for and progress towards the development of a COVID-19 vaccine, which highlights the importance of the integration of innovation systems to address huge health challenges and emergencies. Countries that have paved the way for building R&D capabilities and collaborations with domestic and foreign actors in the biopharmaceutical industry over the years are those that are reaping the benefits of developing a viable and marketable vaccine amidst the COVID-19 pandemic.

**Table 5: Econometric results**

| | Model 1 (GDP) | | | Model 2 (GII) | | | Model 3 (Patents pharma) | | | Model 4 (ICH membership) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **VARIABLES** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** |
| **Quantile** | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 |
| Number of vaccines | 0.195*** | 0.205*** | 0.234*** | 0.194*** | 0.200*** | 0.234*** | 0.191*** | 0.177*** | 0.195*** | 0.192*** | 0.196*** | 0.151** |
| | (0.019) | (0.044) | (0.071) | (0.019) | (0.045) | (0.053) | (0.032) | (0.028) | (0.047) | (0.020) | (0.048) | (0.067) |
| Private-public collaborations | 0.112* | 0.118 | 0.0491 | 0.110* | 0.0976 | 0.0438 | -0.00214 | -0.113 | 0.0051 | 0.0976 | 0.112 | 0.231 |
| | (0.065) | (0.149) | (0.237) | (0.062) | (0.148) | (0.173) | (0.112) | (0.100) | (0.166) | (0.062) | (0.144) | (0.202) |
| Private-private collaboration | 0.151** | 0.0901 | 0.271 | 0.155** | 0.113 | 0.279 | 0.105 | -0.124 | -0.0766 | 0.159** | 0.107 | 0.382* |
| | (0.065) | (0.150) | (0.239) | (0.064) | (0.154) | (0.180) | (0.108) | (0.097) | (0.160) | (0.067) | (0.155) | (0.218) |
| Public-public collaborations | -0.204** | -0.136 | 0.122 | -0.203** | -0.12 | 0.127 | -0.366** | -0.131 | -0.136 | -0.171* | -0.1 | 0.165 |
| | (0.093) | (0.215) | (0.342) | (0.089) | (0.213) | (0.250) | (0.176) | (0.157) | (0.261) | (0.089) | (0.208) | (0.293) |
| Global collaborations | 0.107 | 0.264 | 0.227 | 0.1 | 0.27 | 0.224 | 0.196 | 0.626*** | 0.650* | 0.152 | 0.263 | -0.192 |
| | (0.160) | (0.369) | (0.587) | (0.156) | (0.374) | (0.438) | (0.249) | (0.222) | (0.368) | (0.148) | (0.345) | (0.485) |
| Log GDP per capita | 0.0143 | -0.0105 | -0.00897 | | | | | | | | | |
| | (0.066) | (0.153) | (0.243) | | | | | | | | | |
| Patents in pharmaceuticals | | | | | | | 0.0001*** | 0.0003*** | 0.0003*** | | | |
| | | | | | | | (0.000) | (0.000) | (0.000) | | | |

| | Model 1 (GDP) | | | Model 2 (GII) | | | Model 3 (Patents pharma) | | | Model 4 (ICH membership) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **VARIABLES** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** | **Index** |
| **Quantile** | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 |
| ICH membership | | | | | | | | | | 0.0616 | 0.107 | 0.909* |
| | | | | | | | | | | (0.161) | (0.375) | (0.527) |
| GII ranking | | | | 0.000 | -0.001 | 0 | | | | | | |
| | | | | (0.002) | (0.005) | (0.006) | | | | | | |
| Constant | -0.313 | -0.072 | -0.007 | -0.150 | -0.107 | -0.091 | -0.190 | -0.068 | -0.071 | -0.208* | -0.161 | -0.008 |
| | (0.636) | (1.464) | (2.330) | (0.159) | (0.379) | (0.444) | (0.197) | (0.176) | (0.291) | (0.122) | (0.285) | (0.400) |
| | | | | | | | | | | | | |
| Observations | 40 | 40 | 40 | 38 | 38 | 38 | 39 | 39 | 39 | 40 | 40 | 40 |

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

## 5. Conclusions

The literature on biopharmaceutical innovations focuses on the strategic importance of radical innovations in terms of firm-level competitiveness and the location of R&D collaborators for their creation. Our study introduces another vector to this discussion, namely that the devastating effects of the COVID-19 pandemic can be addressed not by developing radical innovations, but by developing incremental important, even life-saving "rapid innovations" based on swift access to existing knowledge accumulated by countries over time, reflected in their national technological capabilities, and building on past radical innovations – namely, vaccine technology platforms. It follows that the relevance of the location of R&D collaborators within that context is also related to the existing pool of accumulated knowledge and capabilities to address unexpected emergencies. In other words, rapidly and urgently developing a vaccine requires finding collaborators with whom the developers have already established collaborative capabilities. For countries with low levels of readiness for and progress towards developing vaccines, this implies collaborating locally while those with medium and high levels of readiness will collaborate globally. This aspect of our study reinforces the established notion that 'going global' is more efficient for knowledge acquisition than staying local, with the exception that our study demonstrates that this also applies within the context of harnessing knowledge for rapid, important albeit incremental innovations. Our study also provides an econometric basis for claims that have been made by several authors on the types of collaborations underpinning biopharmaceutical organizations' ability to rapidly develop COVID-19 vaccines.

In line with current thinking around innovation as a multi-stakeholder interactive process, the COVID-19 pandemic has reiterated the value of collaboration, particularly in areas related to science, technology, innovation and industrial development. Bump, Friberg and Harper (2021) for example, provide three reasons why collaboration is highly valuable. First, in a heavily interconnected world, collective health, economic and social risks, such as those unleashed by COVID-19, are difficult to manage autonomously. Second, sharing knowledge, experience and other resources contribute to learning and can accelerate progress towards finding solutions to emerging disasters. And third, collaboration can underpin shared understanding and mutual trust in times of increased uncertainty and need. Despite criticisms about the lack of international solidarity in fighting the pandemic, we demonstrate that at the more granular level, global collaborations facilitated the unprecedented speed observed in the development of COVID-19 vaccines which are currently being administered globally.

Moreover, our study shows that the types of collaborations relevant for countries' readiness for and progress towards developing COVID-19 vaccines, are limited or have an advantage due to their context specificities. Thus, countries' ability to develop COVID-19 vaccines, as illustrated by our results, lies in the strength of their national technological and collaborative capabilities. While the institutions and the quality of institutions in China and the U.S. differ considerably, the two countries are leading the race in terms of readiness and progress, among others because they lead across various other economic indicators (such as GDP and world merchandise trade) and in terms of industrial strength. Thus, we can surmise that the strength of industrial policies as captured in the literature on the link between industrial and STI capabilities (Santiago et al., 2020) are crucial factors in the readiness and progress of these two countries. We cannot deduce whether the same is true for linkages between the healthcare system and industrial policy (Mackintosh et al. 2016; Shadlen and Fonseca 2013; Mackintosh et al. 2018). Future studies should explore whether such linkages hold true in the specific case of countries that have successfully developed COVID-19 vaccines.

Our study also raises questions on the relationship between countries' level of readiness and progress (as indicated by the quantile in our regression results) and the nature and rate of inter-organizational collaborations at various stages of vaccine development. Future studies could explore whether collaborations tend to be more formal/informal and frequent/infrequent at early stages of vaccine development under emergency situations, since the science in that case is more important than the technology; whether new sources of knowledge in terms of new collaborations are needed at the discovery and initial characterization stage; whether collaborations take the form of research contracts and R&D outsourcing as organizations move up the clinical phases ladder or whether they are further centralized and kept in-house; and whether organizations are primarily involved in high levels of technology transfer, co-production agreements and marketing during the final clinical trial phase (Phase IV). Santiago and Dutrénit (2012), for example, using evidence from Mexico, illustrate how by decomposing the pharmaceutical innovation process into its different R&D components, the changing nature of determinants for academia-industry collaboration can be identified. Another area of future research specific to the COVID-19 pandemic and similar emergency and crisis situations, which needs to be investigated but was beyond the scope of this paper, relates to the types of global governance schemes and mechanisms necessary to guide and monitor countries whose organizations are engaged in global collaborations. Such schemes and mechanisms are necessary to ensure that countries and their organizations—whose values tend to be competing with foreign ones—honour their engagements within those collaborations in a manner that serves to alleviate the crisis and the suffering of populations.

Finally, while we do not study the innovation and capacity issues involved in the production, manufacturing and worldwide equitable distribution of COVID-19 vaccines, it is nevertheless important to comment on these as they represent important global stakes as the world moves forward from this pandemic. First, the impressive progress achieved by organizations in the development of COVID-19 vaccines illustrates how nations can benefit from investing in research and enhanced biotechnological capabilities (Rao and Srinivas, 2020). The development of vaccines requires strong scientific bases, clinical interfaces and testing contexts, together with a robust manufacturing infrastructure linked to strong public policy goals (Rao and Srinivas, 2020). Second, the crisis has underscores the importance of investing in manufacturing capabilities. The manufacturing of vaccines is not only a complex and costly endeavour (Anderson, 2020), the uneven distribution of manufacturing capabilities across the globe is a major limitation to a faster large-scale deployment of different COVID-19 vaccines, and to guarantee fair and equitable access, particularly for the poor (Mehta, 2020; Twohey, Collins and Thomas 2020).

Gehl, Sampath and Pearman (2021) assert that in order to sustainably build local industrial capabilities in biopharmaceuticals, a combination of factors need to be put in place, including better coordination of vaccine supply in multinational and local firms' production initiatives. This is crucial for ensuring a receptive market for new entrants; fostering a diversified offer of vaccine technologies linked to the complex local epidemiological situation; and securing market certainty through, for example, dedicated public procurement interventions. Thus, to better prepare domestic healthcare systems for crisis like the COVID-19 pandemic, countries need to address capability gaps in areas related to governance, infrastructure, human resources and R&D (de Savigny et al., 2008), and in the ability to draw on manufacturing to address pressing domestic healthcare challenges.

## References


Abecassis, P. & Coutinet, N. (2008) 'Caractéristiques du marché des médicaments et stratégies des firmes pharmaceutiques', *Horizons stratégiques*, 7, 111-139. https://doi.org/10.3917/hori.007.0111

Ahuja, A. (2021, February 16th) 'A universal Covid vaccine may be our best means of escape'. *Financial Times*, https://www.ft.com/content/c6d663e1-9753-4a92-8d7c-599fd0dd45c7.

Archibugi, D., & Bizzarri, K. (2004) 'Committing to vaccine R&D: a global science policy priority'. *Research Policy*, 33(10),1657–1671. https://doi.org/10.1016/J.RESPOL.2004.10.003

Archibugi, D., & Coco, A. (2004) 'A New Indicator of Technological Capabilities for Developed and Developing Countries (ArCo)'. *World Development*, 32(4), 629–654. https://doi.org/10.1016/J.WORLDDEV.2003.10.008

Archibugi, D., & Coco, A. (2005) 'Measuring technological capabilities at the country level: A survey and a menu for choice'. *Research Policy*, 34(2), 175–194. https://doi.org/10.1016/J.RESPOL.2004.12.002

Archibugi, D., Denni, M. and Filippetti, A. (2009) 'The Technological Capabilities of Nations: The State of the Art of Synthetic Indicators'. *Technological Forecasting & Social Change*. 76(7), 917-931 https://doi.org/10.1016/j.techfore.2009.01.002

Arora, A. & Gambardella, A. (1994) 'The changing technology of technological change: general and abstract knowledge and the division of innovative labor', *Research Policy*, 23(5), 523-532. https://doi.org/10.1016/0048-7333(94)01003-X

Arora, A. and Gambardella, A. (1990) 'Complementarity and external linkages: the strategies of the large firms in biotechnology', *The Journal of Industrial Economics*, 38(4), 361-379. https://doi.org/10.2307/2098345

Belderbos, R., Carree, M., Diederen, B., Lokshin, B. and Veugelers, R. (2004) 'Heterogeneity in R&D cooperation strategies', *International Journal of Industrial Organization*, 22(8/9), 1237-1263. https://doi.org/10.1016/j.ijindorg.2004.08.001

Belderbos, R., Grabowska, M., Kelchtermans, S. *et al.* (2021) 'Whither geographic proximity? Bypassing local R&D units in foreign university collaboration'. *J Int Bus Stud*, 52, 1302–1330 . https://doi.org/10.1057/s41267-021-00413-6

Bercovitz, J., Feldman, M. (2007) 'Fishing upstream: firm innovation strategy and university research alliances', *Research Policy*, 36(7), 930-948. https://doi.org/10.1016/j.respol.2007.03.002

Bignami, F., Mattsson, P. and Hoekman, J. (2019) 'The importance of geographical distance to different types of R&D collaboration in the pharmaceutical industry', *Industry and Innovation*, 27(5), 513-537 https://doi.org/10.1080/13662716.2018.1561361

Boseley, S. (2020, December 9th) 'Nine out of 10 in Poor Nations to Miss out on Inoculation as West Buys up Covid Vaccines', *The Guardian*. Retrieved from:

https://www.theguardian.com/society/2020/dec/09/nine-out-of-10-in-poor-nations-to-miss-out-on-inoculation-as-west-buys-up-covid-vaccines.

Branswell, H. (2020, Jun 26th) 'WHO, Partners Unveil Ambitious Plan to Deliver 2 Billion Doses of Covid-19 Vaccine to High-Risk Populations', *STAT*. Retrieved from:https://www.statnews.com/2020/06/26/who-partners-unveilambitious- plan-to-deliver-2-billion-doses-of-covid-19-vaccine-to-high-risk-populations/.

Bump, J.B., Friberg, P. and Harper, D.R. (2021) 'International Collaboration and COVID-19: What Are We Doing and Where Are We Going?', *BMJ*, 372(180). https://doi.org/10.1136/bmj.n180.

*CEPI*. [online] https://cepi.net/.

Cohen, w. & Levinthal, D. (1990) 'Absorptive capacity: a new perspective on learning and innovation', *Administrative Science Quarterly*, 35(1), 128-152. https://doi.org/10.2307/2393553

de Savigny, D., Kasale, H., Mbuya, C. and Reid., G. (2008) *Fixing Health Systems*. 2nd ed. Ottawa, Canada: IDRC. https://www.idrc.ca/en/book/fixing-health-systems-2nd-edition.

Druedahl, L.C., Minssen, T., Price, W. N. (2021) 'Collaboration in times of crisis: A study on COVID-19 vaccine R&D partnerships', *Vaccine*, 39(42), 6291-6295. https://doi.org/10.1016/j.vaccine.2021.08.101

European Commission. (2021*) Coronavirus research and innovation [online]*. EC, European Union. https://ec.europa.eu/info/research-and-innovation/research-area/healthresearch-and-innovation/coronavirus-research-and-innovation_en.

European Medicines Agency. (2021) *Comirnaty [online]*. EMA, European Union. https://www.ema.europa.eu/en/medicines/human/EPAR/comirnaty.(Accessed 2021)

Faulkner, W. & Senker, J. (1994) 'Making sense of diversity: public-private sector research linkage in three technologies', *Research Policy*, 23, 673-695. https://doi.org/10.1016/0048-7333(94)90017-5

Forman, R., Shah, S., Jeurissen, P., Jit, M., Mossialos, E. (2021) 'COVID-19 vaccine challenges: What have we learned so far and what remains to be done?', *Health Policy*, 125(5), 553-567. https://doi.org/10.1016/j.healthpol.2021.03.013

Frenz, M. & Ietto-Gillies, G. (2009) 'The impact on innovation performance of different sources of knowledge: evidence from the UK Community Innovation Survey'. *Research Policy*, 38 (7), 1.125-1.135. https://doi.org/10.1016/j.respol.2009.05.002

GAVI (2020) '5 reasons why pandemics like COVID-19 are becoming more likely'. https://www.gavi.org/vaccineswork/5-reasons-why-pandemics-like-covid-19-are-becoming-more-likely.

Gehl Sampath, G. S., and Pearman, J. (2021) 'Local Production of COVID 19 Vaccines: A Strategy for Action'. *Global Policy*, August. https://www.globalpolicyjournal.com/sites/default/files/pdf/Gehl%20Sampath%20and%20Pearman%20-

%20Local%20Production%20of%20COVID%2019%20Vaccines%2C%20A%20Strategy%20for%20Action_0.pdf

Gilsing, V. & Nooteboom, B. (2006), 'Exploration and exploitation in innovation systems: the case of pharmaceutical biotechnology', *Research Policy*, 35(1), 1-23 https://doi.org/10.1016/j.respol.2005.06.007

Hess, A & Rothaermel, F. (2011) 'When are assets complementary? Star scientists, strategic alliances, and innovation in the pharmaceutical industry', *Strategic Management Journal*, 32(8), 895-909. https://doi.org/10.1002/smj.916

Hu, Y., Scherngell, T., Qiu, L. and Wang, Y. (2015) 'R&D internationalisation patterns in the global pharmaceutical industry: evidence from a network analytic perspective', *Technology Analysis & Strategic Management*, 27(5), 532-549. https://doi.org/10.1080/09537325.2015.1012058

Jasso-Villazul, J., & Torres-Vargas, A. (2021) 'New public-private collaboration mechanisms for the development and access to the COVID-19 vaccine: A perspective from grounded theory', *Contaduría y Administración*, 65(5). http://dx.doi.org/10.22201/fca.24488410e.2020.3134

Jensen, M. B., Johnson, B., Lorenz, E., & Lundvall, B. Å. (2007) Forms of knowledge and modes of innovation. *Research Policy*, *36*(5), 680–693. https://doi.org/10.1016/J.RESPOL.2007.01.006.

Lall, S. (1992) 'Technological capabilities and industrialization', *World Development*, 20(2), 165-186. https://doi.org/10.1016/0305-750X(92)90097-F

Lee, K. and Malerba, F. (2017) 'Theory and Empirical Evidence of Catch-up Cycles and Changes in Industrial Leadership'. *Research Policy* 46 (2): 337. https://doi.org/10.1016/j.respol.2016.09.008.

Mackintosh, M., Mugwagwa, J., Banda, G., Tibandebage, P., Tunguhole, J., Wangwe, S. and Njeru, M.K. (2018) 'Health-Industry Linkages for Local Health: Reframing Policies for African Health System Strengthening'. *Health Policy and Planning* 33 (4): 602–10. https://doi.org/10.1093/heapol/czy022.

Mackintosh, M., Tibandebage, P., Kungu, J.K, Njeru, M.K and Israel, C. (2016) 'Health Systems as Industrial Policy: Building Collaborative Capabilities in the Tanzanian and Kenyan Health Sectors and Their Local Suppliers'. In Making Medicines in Africa: The Political Economy of Industrializing for Local Health, edited by Maureen Mackintosh, Geoffrey Banda, Paula Tibandebage, and Watu Wamae, 147–65. *International Political Economy Series.* London: Palgrave Macmillan UK. https://doi.org/10.1007/978-1-137-54647-0_9.

Malerba, F. & Orsenigo, L. (2015), 'The evolution of the pharmaceutical industry', *Business History*, 57(5), 664-687. https://doi.org/10.1080/00076791.2014.975119

Mehta, A. (2020) 'COVID-19 Vaccine Deals Risk Skewing Supply'. *Chemistry World* [online] 25 September. https://www.chemistryworld.com/news/COVID-19-vaccine-deals-risk-skewing-supply/4012474.article.

Mowery, D. and Sampat, B. (2005) 'Universities in national innovation systems', *The Oxford Handbook of Innovation*. https://doi.org/10.1093/oxfordhb/9780199286805.003.0008.

Nature (2021a) 'Partnerships in a crisis', *Nature* [online]. https://www.nature.com/articles/d42473-021-00250-z.

Nature (2021b) 'Research collaborations bring big rewards: the world needs more', *Nature* 594, 301-302. https://doi.org/10.1038/d41586-021-01581-z.

Nelson, R. (1992) 'National Innovation Systems: A Retrospective on a Study', *Industrial and Corporate Change*, 1(2),347–374. https://doi.org/10.1093/icc/1.2.347.

OECD (2002) *Benchmarking Industry-Science Relationships*, OECD Publications, Paris, https://doi.org/10.1787/9789264175105-en.

Parrilli, M. D., & Alcalde Heras, H. (2016) STI and DUI innovation modes: Scientific-technological and context-specific nuances. *Research Policy*, *45*(4), 747–756. https://doi.org/10.1016/J.RESPOL.2016.01.001

Pavitt, K. (1984) 'Sectorial patterns of technical change: towards a taxonomy and a theory'. *Research Policy*, 13(6), 343-373.https://doi.org/10.1016/0048-7333(84)90018-0

Perkmann, M., Salandra, R., Tartari, V., McKelvey, M., & Hughes, A. (2021) Academic engagement: A review of the literature 2011-2019. *Research Policy*, *50*(1), 104114. https://doi.org/10.1016/J.RESPOL.2020.104114.

Radanliev, P., De Roure, D., Walton, R. (2020) 'Data mining and analysis of scientific research data records on Covid-19 mortality, immunity, and vaccine development - In the first wave of the Covid-19 pandemic', *Diabetes & Metabolic Syndrome Clinical Research & Reviews*, 14(5), 1121-1132. https://doi.org/10.1016/j.dsx.2020.06.063

Randall, T., Sam, C., Tartar, A., Murray, P., and Cannon, C. (2021, November 21st) 'More Than 7.46 Billion Shots Given: Covid-19 Tracker'. *Bloomberg*. Retrieved from:https://www.bloomberg.com/graphics/covid-vaccine-tracker-global-distribution/

Rao, P. and Srinivas, S. (2020) 'Economics and Public Health: A Case for Interdisciplinary Cohesion in the Time of Coronavirus'. *Innogen*. https://www.innogen.ac.uk/sites/default/files/2020-04/The%20need%20for%20economics%20involvement%20in%20public%20health%20-%20Lessons%20from%20the%20Coronavirus.pdf.

Rodriguez-Fuentes, G., Santiago, F. Rodríguez, I and Jover, J.N. (2017) 'La Creación de La Industria Cubana de Zeolitas Naturales: Un Caso de Universidad Emprendedora'. In *Vinculación Universidad-Sector Productivo Para Fortalecer Los Sistemas Nacionales de Innovación: Experiencias de Cuba, México y Costa Rica.*, edited by Gabriela Dutrénit and Jorge Núñez Jover, 123–51. Habana: Universidad de la Habana.

Rosenberg, N. and Nelson, R. (1994), 'American universities and technical advance in industry', *Research Policy*, 23(3), 323-348. https://doi.org/10.1016/0048-7333(94)90042-6.

Santiago, F. (2010) 'Governing Ethical Clinical Research in Developing Countries: Exploring the Case of Mexico' *Science and Public Policy*, 37(8), 583–96. https://doi.org/10.3152/030234210X12767691861010.

Santiago, F., De Fuentes, C., Peerally, J.A. and Larsen, J (2020) 'Investing in Innovative and Productive Capabilities for Resilient Economies in a Post-COVID-19 World'. *International Journal of Technological Learning, Innovation and Development* 12 (2), 153–67. https://doi.org/doi:10.1504/IJTLID.2020.110623.

Santiago, F., Dutrénit, G. (2012) 'Determinants of PRO-Industry Interactions in Pharmaceutical R&D: The Case of Mexico.' In *Innovation Systems and Capabilities in Developing Regions: Concepts, Issues and Cases*, edited by Abiodun Egbetokun, Boladale Adebowale, Willie Siyanbola, and Olumuyiwa Olamade, 251–75. Gower Publishing, Ltd. http://collections.unu.edu/view/UNU:250.

Scandura, A. (2016) 'University-industry collaboration and firms' R&D effort'. *Research Policy*, 45(9), 1.907-1.922. https://doi.org/10.1016/j.respol.2016.06.009

Shadlen, K.C. and Massard da Fonseca, E. (2013) 'Health Policy as Industrial Policy Brazil in Comparative Perspective'. *Politics & Society* 41 (4), 561–87. https://doi.org/10.1177/0032329213507552.

Soh, P-H. and Subramanian, A. (2014) 'When do firms benefit from university-industry R&D collaborations? The implications of firm R&D focus on scientific research and technological recombination', *Journal of Business Venturing*, 29(6), 807-821. https://doi.org/10.1016/j.jbusvent.2013.11.001

Srinivas, S. (2015) 'Pathways Less Traveled: From Scarcity to Solutions'. *UNICEF. The State of the World's Children 2015* [online]. 2015. https://sowc2015.unicef.org/stories/pathways-less-traveled-including-children-in-overcoming-scarcity/.

Srinivas, S. (2016) 'Healthy Industries and Unhealthy Populations: Lessons from Indian Problem-Solving'. In *Making Medicines in Africa: The Political Economy of Industrializing for Local Health*, edited by Maureen Mackintosh, Paula Tibandebage, Watu Wamae, and Geoffrey Banda, 183–99. https://doi.org/10.1007/978-1-137-54647-0_11.

Stata Technical Bulletin. (1992) *A publication to promote communication among Stata users* [online], STB-9, Scottsdale. https://www.stata.com/products/stb/journals/stb9.pdf .

Subramanian, A., Lim, K. and Soh, P. (2013) 'When birds of a feather don't flock together: different scientists and the roles they play in biotech R&D alliances', *Research Policy*, 42(3), 595-612. https://doi.org/10.1016/j.respol.2012.12.002.

Steinmo, M. (2015) Collaboration for Innovation: A Case Study on How Social Capital Mitigates Collaborative Challenges in University–Industry Research Alliances. *Industry and Innovation*, *22*, 1–28. https://doi.org/10.1080/13662716.2015.1105127.

Teece, D. (2007) 'Explicating dynamics capabilities: the nature and microfoundations of (sustainable) enterprise performance', *Strategic Management Journal*, 28(13), 1319-1350.https://doi.org/10.1002/smj.640.

Tidd, J., Bessant, J. and Pavitt, K. (2001) *Managing Innovation: integrating Technological, Market and Organizational Change*, 2nd ed., John Wiley and Sons, Chichester, pp. 37-63. ISBN: 978-1-119-37945-4

Triulzi, G., Pyka, A. and Scholz, R. (2014) 'R&D and knowledge dynamics in university-industry relationships in biotech and pharmaceuticals: an agent-based model'. *International Journal of Biotechnology*, 13(1-3), 137-179. https://doi.org/10.1504/IJBT.2014.059650

Twohey, M., Collins, K. and Thomas, K. (2020, December 15th) 'With First Dibs on Vaccines, Rich Countries Have "Cleared the Shelves"'. *The New York Times*, Online edition.https://www.nytimes.com/2020/12/15/us/coronavirus-vaccine-doses-reserved.html.

United Nations (2020a) *General Assembly Adopts Omnibus Resolution Calling for Holistic COVID-19 Response, among 3 Passed on Global Health Threats, Malaria* [online]. UN. https://www.un.org/press/en/2020/ga12262.doc.htm.

Unknown Author. (2020) 'Intensifying Vaccine Production'. *Bulletin of the World Health Organization*, 98(5), 302–3. https://doi.org/10.2471/BLT.20.020520.

US Food and Drug Administration, a (2021) *FDA Approves First COVID-19 Vaccine [online]*. FDA, United States. https://www.fda.gov/news-events/press-announcements/fda-approves-first-COVID-19-vaccine.

US Food and Drug Administration, b (2021) *Emergency Use Authorization [online]*. FDA, United States. https://www.fda.gov/emergency-preparedness-and-response/mcm-legal-regulatory-and-policy-framework/emergency-use-authorization (Accessed 2021)

Wang, J. and Hong, N. (2020) 'The COVID-19 research landscape: Measuring topics and collaborations using scientific literature', *Medicine*, Vol. 99(43), e22849. https://doi.org/10.1097/MD.0000000000022849

World Health Organization (2020) *COVAX, The Act-Accelerator Vaccines Pillar* [online], WHO.https://www.who.int/publications/m/item/covax-the-act-accelerator-vaccines-pillar.

World Health Organization (2021) *The access to COVID-19 tools (ACT) accelerator* [online], WHO. https://www.who.int/initiatives/act-accelerator.

Zukauskaite, E., Trippl, M. and Plechero, M. (2017) 'Institutional Thickness Revisited', *Economic Geography*, 93(4), 325-345, https://doi.org/10.1080/00130095.2017.1331703.

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna International Centre · P.O. Box 300 9 · 1400 Vienna · Austria
Tel.: (+43-1) 26026-0 · E-mail: info@unido.org
www.unido.org