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RESEARCH ARTICLE

Lessons from COVID-19

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ABSTRACT

COVID-19 was one of the costliest and deadliest pandemics in the recent history of pandemics. Despite many warnings, the world was not prepared for it. The complexity of the nature of the virus and weak national health systems made monitoring of its progress difficult, despite the leadership that the World Health Organization displayed. This paper reviews the origins of COVID-19 and the human and financial costs of its spread, even among developed countries. Vaccines were an important innovation emerging from the tragedy that illustrated the importance of international cooperation between developed and developing countries and offered important lessons for the future. This paper makes the case for continued development and investment of health systems both in developing and developed countries as a critical pillar of development.

1. Introduction

There have been 249 pandemics in the world history starting from 1200 BC, according to Baum[1]. Among these, COVID-19 (coronavirus disease 2019) was one of the deadliest and extraordinary global epidemics. Bill Gates has called it a horrific global fire, hopefully "a once-in-a-century pandemic" that will not recur in some form or another for the rest of the century[2-3]. Gates had been warning of a deadly epidemic for years. In 2015, he said we were not ready[4]; in 2017, he told CBS News that the impact of a huge epidemic would be phenomenal, because all the supply chains would break down[5]. In 2022, at the Foundation Munich Security Conference, citing the exemplary example of Australia, he stressed that, unlike in the case of climate change, the cost of being prepared for a global pandemic is not astronomical. "Fire preparedness," in the case of an epidemic, is quite possible—he has argued and called for the establishment of a Global Epidemic Response and Mobilization (GERM) team, much like a fire prevention team. Noting how much work was begun after the Second World War, he expressed hope that steps would be taken soon, while memories are fresh following the COVID-19 epidemic. He advocates a GERM team under the World Health Organization (WHO). Had we stopped the epidemic in the first few weeks, COVID-19 could have been contained much better than it was[6].

1.1 OUTLINE OF THE PAPER

The paper outlines the cumulative costs of COVID-19. Using WHO data, it reviews some recent evidence on the incidence of COVID-19 in a diverse set of developed and developing countries. It reviews the origins of the pandemic, the complex nature of its diversity and its spread, and implications for future action to contain, if not combat it before it becomes a pandemic.

Cutler and Summers estimated the cumulative financial costs of the COVID-19 pandemic, as related to lost output and health reduction to be more than US$16 trillion, or roughly 90 percent of the annual GDP of the United States[7]. For a family of four, the estimated loss would be nearly US$200,000. About half of this amount is the lost income from the COVID-19-induced recession; the remainder is the economic impact of shorter and less healthy life. To reduce costs, increased investment in preventive health can help bridge the huge health gap between the rich and the poor classes, countries, and regions.

Such a response calls for a combination of capacities in diagnostics, therapeutics, and vaccination production and delivery. Through diagnostics, we need to stop the epidemic before we need vaccines. We need easier delivery of single vaccines, which can be useful for a variety of types of viruses. In addition, for this disease monitoring needs to be improved.

1.2 COVID-19: THE PANDEMIC'S ORIGINS, IMPACT, AND ONGOING CHALLENGES

COVID-19, officially named SARS-CoV-2, emerged in December 2019 as a previously unknown strain of coronavirus causing respiratory illness. Initially designated 2019-nCoV, it was formally named by the International Committee on Taxonomy of Viruses and the World Health Organization as SARS-CoV-2 and COVID-19, respectively. Determining the exact origin of the virus remains a matter of ongoing investigation, with zoonotic spillover being the most likely source. Coronaviruses (CoV), a large family of viruses known to infect humans and animals, cause a diverse range of illnesses, from the common cold to more severe diseases like Middle East Respiratory Syndrome (MERS) and SARS (Severe Acute Respiratory Syndrome). Therefore, precise monitoring of its incidence and spread is critical.

The first confirmed cases of COVID-19 were reported in Wuhan, China, in December 2019. Patients presented with respiratory symptoms, and many had visited the Huanan Seafood Wholesale Market. The virus's rapid global spread prompted the WHO to declare COVID-19 a global pandemic in March 2020, a bold move, impacting every country on the planet.

COVID-19 primarily spreads through respiratory droplets, generated when an infected individual coughs or sneezes. Indirect transmission through contact with contaminated surfaces is also possible. The disease manifests with a spectrum of symptoms, ranging from mild to severe. While some individuals remain asymptomatic, others can experience serious illness or even death. Fever, cough, shortness of breath, fatigue, muscle aches, headache, sore throat, loss of taste or smell, congestion, nausea, vomiting, and diarrhea are the most commonly reported symptoms. In severe cases, complications like pneumonia, acute respiratory distress syndrome, and multisystem inflammatory syndrome in children (MIS-C) may arise.

Although no specific treatment for COVID-19 exists, various preventive measures have proven effective in mitigating its spread. These include vaccination, mask-wearing in public indoor settings, social distancing, frequent handwashing and sanitizing,

and avoiding close contact with individuals exhibiting symptoms.

COVID-19 has had a profound impact on the world, causing millions of deaths and disrupting households, economies, societies, and health care systems globally. The pandemic also exposed vulnerabilities in global preparedness for health crises. Researchers continue to investigate the virus, focusing on developing new prevention and treatment strategies. Emerging variants of the virus pose additional challenges, requiring continuous research and development of new vaccines and therapies. As COVID-19 remains an evolving situation, seeking the latest information on prevention, treatment, and vaccination efforts from authoritative sources like WHO and the Centers for Disease Control and Prevention (CDC) remains critical, and in turn, ensuring that they and member countries have the capacity to monitor these diseases. WHO's effectiveness is as good as its weakest link.

1.3 UNVEILING THE DIVERSITY OF CORONAVIRUSES: FROM MORPHOLOGY TO GENOMIC CLASSIFICATION

CoV, characterized by their distinctive crown-like appearance under an electron microscope, constitute a vast family of positive-sense, single-stranded RNA viruses. Originally identified in 1966, by Tyrell and Bynoe, who isolated them from individuals afflicted with the common cold, the nomenclature "coronaviruses" was aptly chosen due to the spherical virions displaying surface projections reminiscent of a solar corona, drawing from the Latin word for crown, *coronam*[8].

Within the Nidovirales order, Coronaviridae stands as a prominent family, further classified into the Torovirinae and Coronavirinae subfamilies. The Coronavirinae subfamily, in turn, encompasses the genetically diverse alphaCoV (Alphacoronavirus), betaCoV (Beta coronavirus), deltaCoV (Deltacoronavirus), and gammaCoV (Gammacoronavirus) variants[9]. The Betacoronavirus genus, exhibiting considerable diversity, is subdivided into five distinct lineages[10]. Genomic studies reveal that rodents and bats serve as genetic sources for Alphacoronavirus and Betacoronavirus, while avian species harbor Gammacoronavirus and Deltacoronavirus[11]. Alphacoronavirus and Betacoronavirus primarily contribute to respiratory diseases in humans and gastroenteritis in animals, whereas Gammacoronavirus and Deltacoronavirus predominantly affect avian species, occasionally crossing over to cause infections in mammals[12]. Notably, six coronaviruses have been identified in human beings, including HCoV-229E and HCoV-NL63 from the Alphacoronavirus types, and HCoV-HKU1, HCoV-OC43, SARS-CoV, and MERS-CoV from the Betacoronavirus types, each presenting unique challenges and implications for public health[13].

1.4 COMPLEX LANDSCAPE OF SARS-COV-2 VARIANTS: FROM MOLECULAR MECHANISMS TO PUBLIC HEALTH IMPLICATIONS

SARS-CoV-2, the causative agent of the ongoing COVID-19 pandemic, exhibits a notable capacity for genetic evolution, giving rise to a multitude of variants that diverge from the original strain[14]. The virus's entry into host cells is facilitated by its spikes binding with angiotensin-converting enzyme 2 (ACE2), a crucial step in initiating infection. This process is contingent upon the priming of the glycoprotein spike by the TMPRSS2 protease, an enzyme essential for effective attachment to ACE2[15-16]. Once inside the host cell, the viral genome RNA is released into the cytoplasm, undergoes transcription, and subsequently translation, orchestrating the viral replication cycle[17].

Since March 2020, a proliferation of SARS-CoV-2 variants has been identified, prompting the classification of some as Variants of Concern (VOCs). These VOCs exhibit traits such as heightened virulence or transmissibility, reduced neutralization by antibodies from vaccination or prior infection, evasion of detection, or diminished vaccine efficacy. WHO and the CDC have responded to the evolving landscape by instituting a categorization system, distinguishing variants into Variants of Interest (VOIs) and VOCs. This systematic approach aims to facilitate a nuanced understanding of the diverse variants, enabling more targeted public health responses to effectively manage and mitigate the impact of SARS-CoV-2 variants on the ongoing global health crisis.

1.4.1 Variants of Concern: A Growing Threat to Global Public Health

The emergence of SARS-CoV-2 variants has posed a significant challenge to global efforts to control the COVID-19 pandemic. Among these variants, a subset has been designated as VOCs, due to their potential for increased transmissibility, decreased susceptibility to vaccines or therapeutic interventions, and greater virulence. Below we discuss five of the most prominent VOCs: Alpha (B.1.1.7), Beta (B.1.351), Gamma (P.1), Delta (B.1.617.2), and Omicron (B.1.1.529).

Alpha variant (B.1.1.7), first identified in the United Kingdom in late December 2020, quickly gained notoriety for its increased transmissibility, ranging from 43% to 82% higher than previous SARS-CoV-2 variants. By the end of December 2020, the Alpha variant had made its presence known in the United States, marking the beginning of its global impact[18-19].

The Beta variant (B.1.351), originating in South Africa in October 2020, introduced numerous spike mutations and emerged as a key player in the second wave of COVID-19. Its detection in the United States, by the end of January 2021, raised concerns due to its higher transmission risk and decreased susceptibility to neutralization by convalescent/post-vaccination sera and monoclonal antibody treatment[20-21].

The Gamma variant (P.1), discovered in Brazil in December 2020 and reported in the United States in January 2021, demonstrated potentially decreased neutralization by convalescent/post-vaccination sera and monoclonal antibody treatment, further complicating the landscape of SARS-CoV-2 variants[22].

The **Delta variant (B.1.617.2)**, initially identified in India in December 2020, gained infamy as the catalyst behind the devastating second wave of COVID-19 in India in April 2021. Classified as a VOI initially, its rapid global spread prompted WHO to reclassify it as a VOC in May 2021. This highly transmissible variant proliferated in the United States and various parts of Europe.

The most recent addition to the list of VOCs is the **Omicron variant (B.1.1.529)**, first reported in South Africa on November 24, 2021. Within two days, WHO declared Omicron a VOC, noting its high mutational load, surpassing even the Delta variant[23]. The 3D image analysis by Italian scientists highlighted concentrated mutations in the spike (S) protein, crucial for viral entry into human cells[24]. Cases of the Omicron variant have rapidly spread globally, sparking widespread concern and prompting stringent travel restrictions in several countries. Cases of the Omicron variant have been found in Botswana, Israel, and Hong Kong. Belgium reported Europe's first case of the Omicron variant, followed by Germany and Italy. And the United Kingdom reported their two cases of the Omicron variant on November 27, 2021. Denmark, on November 28, reported two cases of Omicron in travelers from South Africa. The continuous monitoring and understanding of these VOCs are imperative for adapting public health measures and refining vaccination strategies in the face of an ever-evolving viral landscape.

1.4.2 Exploring Variants of Interest in the SARS-CoV-2 Landscape

VOIs within the realm of SARS-CoV-2 represent a dynamic facet of the ongoing COVID-19 pandemic, characterized by specific genetic markers associated with potential alterations in virulence, transmissibility, neutralization of antibodies, detection evasion, or reduced therapeutic and vaccine efficacy. In an epidemiological update on June 22, 2021, WHO identified seven VOIs, each having distinctive features that warranted attention and scrutiny.

Among the designated VOIs, the **Epsilon variants (B.1.427 and B.1.429)** emerged in the United States in June 2020, swiftly escalating to encompass over 50% of reported cases between September 1, 2020, and January 29, 2021. This variant demonstrated an alarming 18.6–24% increase in transmission, compared to preceding strains, prompting the CDC to classify it as a VOC in the United States, due to its heightened transmissibility[25].

The **Zeta variant (P.2)**, originating in Brazil in April 2020, features spike mutations and has been labelled a VOI by both WHO and the CDC. Notably, it exhibits reduced neutralization by antibody therapies and a potential impact on vaccine efficacy, marking it as a variant of interest with implications for public health strategies.

The Eta **(B.1.525)** and Iota **(B.1.526)** variants, discovered in New York in November 2020, bear spike mutations and have been designated as VOIs by the CDC and WHO, due to the variants' potential to decrease neutralization by antibody therapies and vaccines. These variants underscore the importance of continuous surveillance to monitor their prevalence and impact on public health interventions.

The **Theta variant (P.3)**, also known as GR/1092K.V1, first identified in Japan and the Philippines in February 2021, showcases spike mutations and is categorized as a VOI by WHO. Similarly, the Kappa variant (B.1.617.1), discovered in India in December 2021, has earned VOI status from both the CDC and WHO, necessitating ongoing research and vigilance to comprehend its implications.

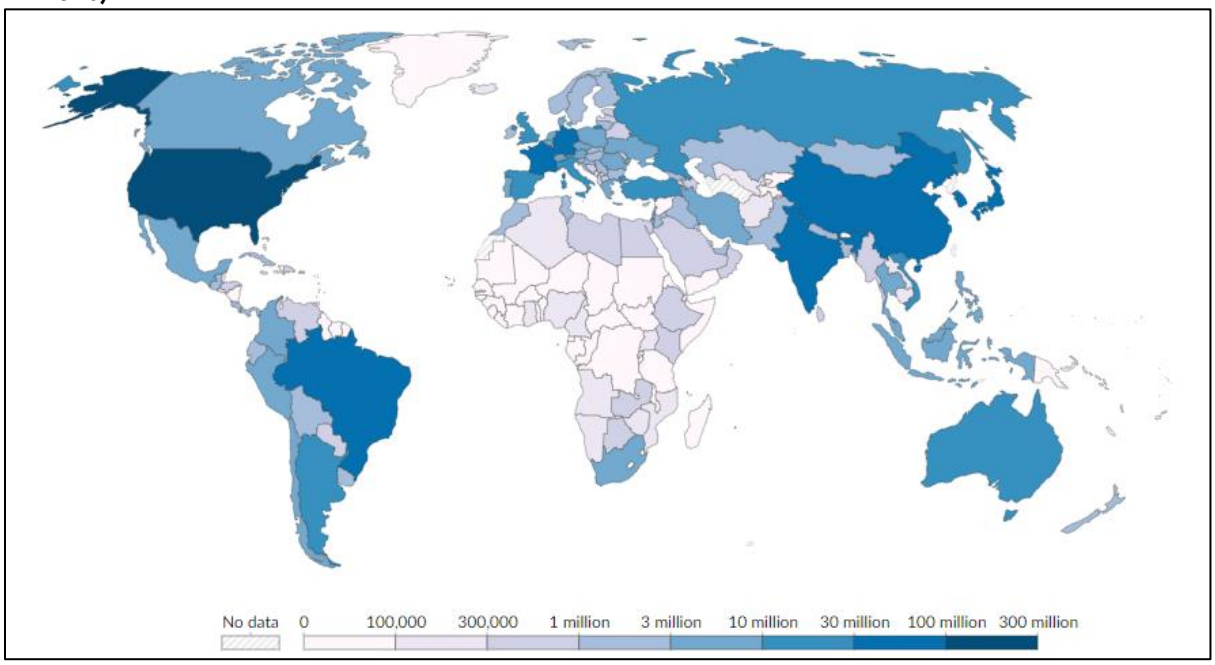
Finally, the **Lambda variant (C.37)**, initially found in Peru, gained attention as a WHO-designated VOI in June 2021, due to its high prevalence in

South America. These VOIs collectively contribute to the evolving narrative of SARS-CoV-2 variants, emphasizing the need for continued monitoring, research, and adaptive public health measures to address the challenges posed by the dynamic viral strains.

2. Geographical spread of total COVID-19 cases

Globally, the total number of confirmed COVID-19 cases was 773 million from January 5, 2020, to December 31, 2023. Due to limited testing, the number of confirmed cases is lower than the true number of infections. Map 1 shows varied outcomes across different parts of the world in the face of a common threat. It is noteworthy that the United States and in European Union, with high per capita income, had high incidence of confirmed cases. The European Union borrowed funds to set aside a whopping €807bn (US$781bn) for a recovery fund, set up in 2020 to help poorer states. Now interest rates are much higher, budgets tighter, and other shocks, such as the war in Ukraine, are also weighing on EU members. At a meeting of finance ministers, the costs were to be determined and the final decision by EU leaders was to be made[26].

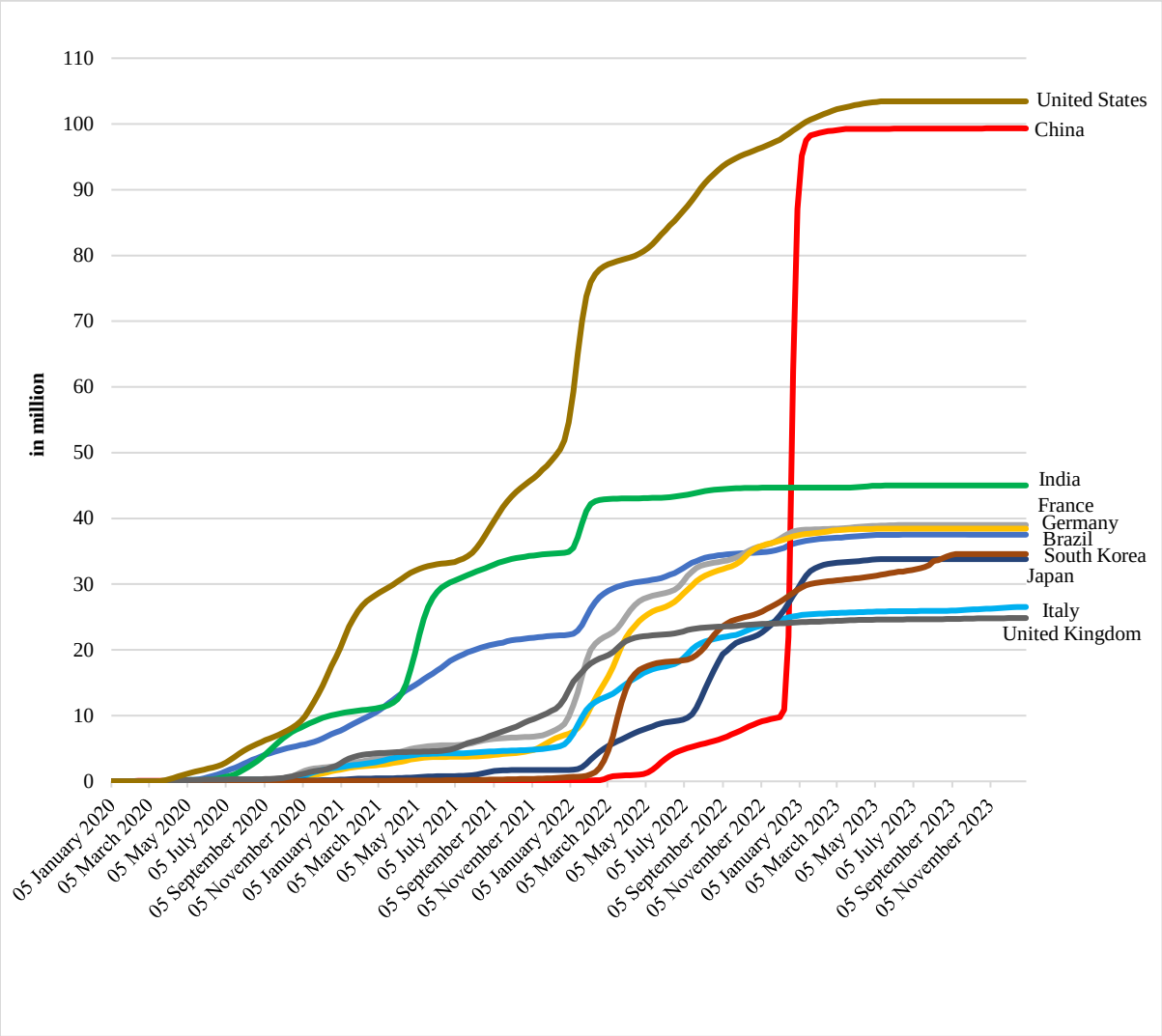
Map 1: Confirmed COVID-19 Cases (January 05, 2020—December 31, 2023) across Countries (in millions)



Source: WHO COVID-19 Dashboard.

To present this analysis, we rely extensively on WHO data. The top 10 COVID-19-affected countries, in terms of numbers of cases, contributed 63% of the total global cases. The United States led the list with over 103 million cases, emphasizing the severity of the situation in the country. China followed closely with 99 million cases, which sharply increased at the end of 2022. India's position, as the third highest with 45 million cases, is indicative of the challenges it faces in managing the pandemic in its densely populated areas. European countries, such as France (39 million), Germany (38 million), Italy (26 million), and the United Kingdom (25 million), also appear in the top 10 as the 4th, 5th, 9th, and 10th positions, respectively, emphasizing the widespread impact of the virus across continents. Brazil is in 6th position with 38 million cases. South Korea (35 million) and Japan (34 million) are placed in 7th and 8th positions, respectively (Figure 1).

Figure 1: Cumulative Confirmed COVID-19 Cases (January 5, 2020–December 31, 2023) in Top Ten Countries (in millions)



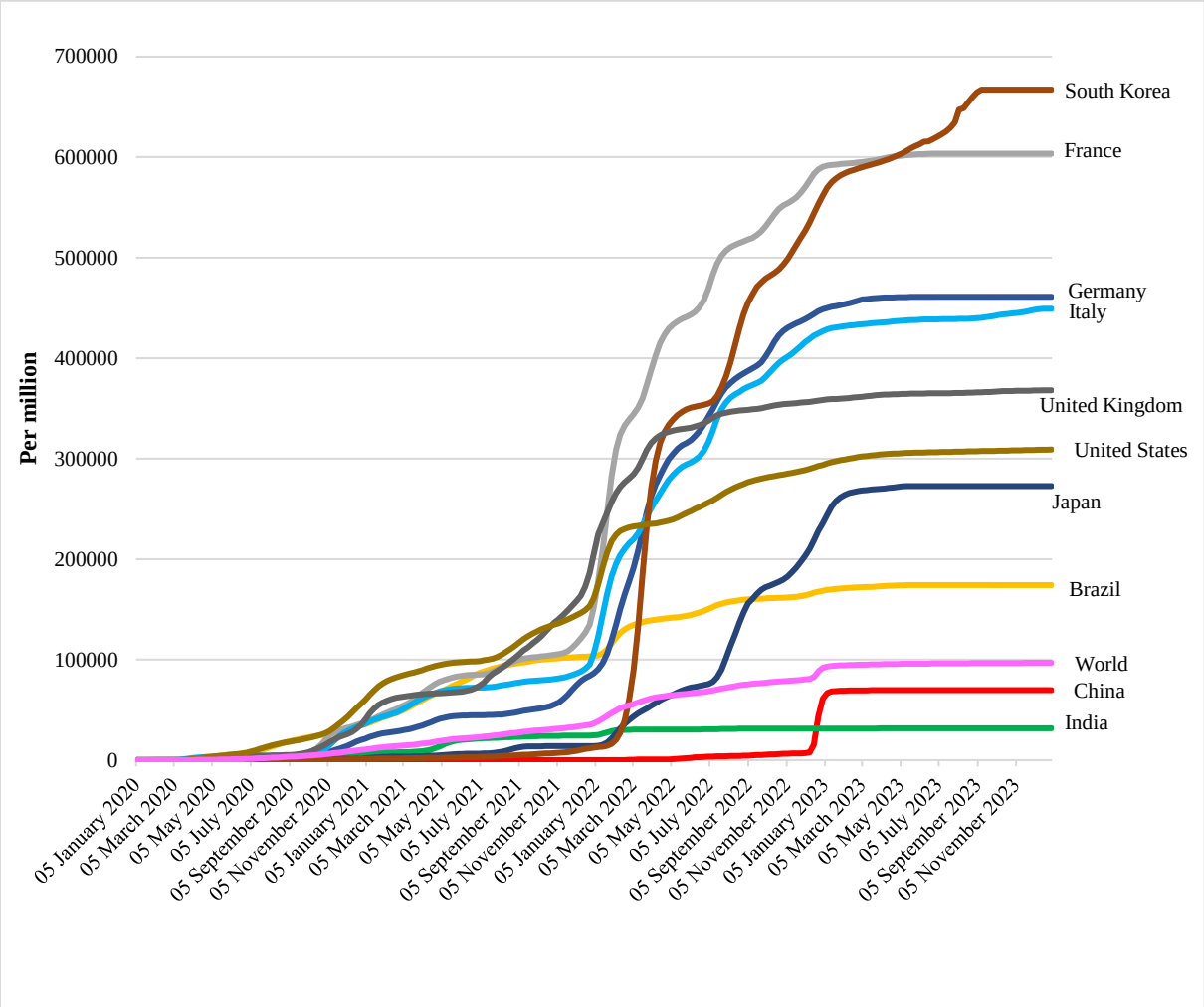
Source: Based on WHO COVID-19 Dashboard Data.

The highest number of COVID-19 cases reported in the United States was around mid-January 2022, in China around the end of December 2022, in India the second week of May 2021, in France at the end of January 2022, in Germany at the end of March 2022, in Brazil in early February 2022, in South Korea during the third week of March 2022, in Japan at the end of August 2022, in Italy after mid-January 2022, and in the United Kingdom in early January 2022. China's steep rise is unclear, except as a reporting delay.

2.1. COVID-19 CASES PER MILLION POPULATION

If we look at cases per million population of the top 10 countries, South Korea (0.67 million) is top among them, followed by France (0.6 million), Germany (0.46 million), Italy (0.44 million), the United Kingdom (0.37 million), the United States (0.31 million), Japan (0.27 million), Brazil (0.18 million), China (0.07 million), and India (0.03 million). Globally, 0.1 million cases have been reported per million population (Figure 2).

Figure 2: Cumulative Confirmed COVID-19 Cases per Million Population (January 5, 2020–December 31, 2023) by Top Ten Countries with COVID-19 Cases

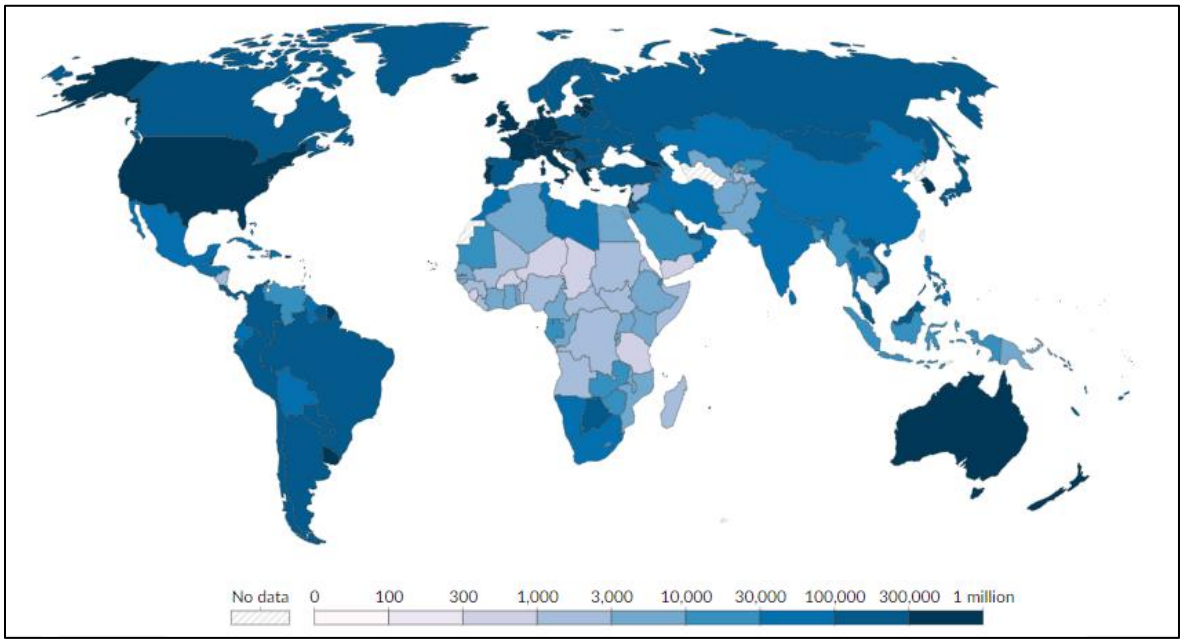


Source: Based on WHO COVID-19 Dashboard Data.

Map 2 presents how confirmed COVID-19 cases per million population are distributed globally. In terms of confirmed COVID-19 cases per million population, the top 10 countries are Cyprus (0.74 million), followed by San Marino (0.73 million), Brunei (0.70 million), Austria (0.68 million), South Korea (0.67 million), Slovenia (0.63 million), Gibraltar (0.63 million), Martinique (0.63 million), France (0.60 million), and Andorra (0.60 million). Notably, South Korea and France are among the top 10 with 5th and 9th positions, respectively, in per million cases, also.

Among the other top 10 countries most affected by total number of COVID-19 cases, Germany placed in 35th position (0.46 million), followed by Italy (42nd, 0.44 million), the United Kingdom (55th, 0.37 million), the United States (64th, 0.31 million), Japan (73rd, 0.27 million), Brazil (101st, 0.18 million), China (148th, 0.07 million), and India (168th, 0.03 million), out of total 230 countries for which data has been reported in terms of COVID-19 cases per million population.

Map 2: Confirmed COVID-19 Cases per Million Population (January 5, 2020–December 31, 2023) across Countries

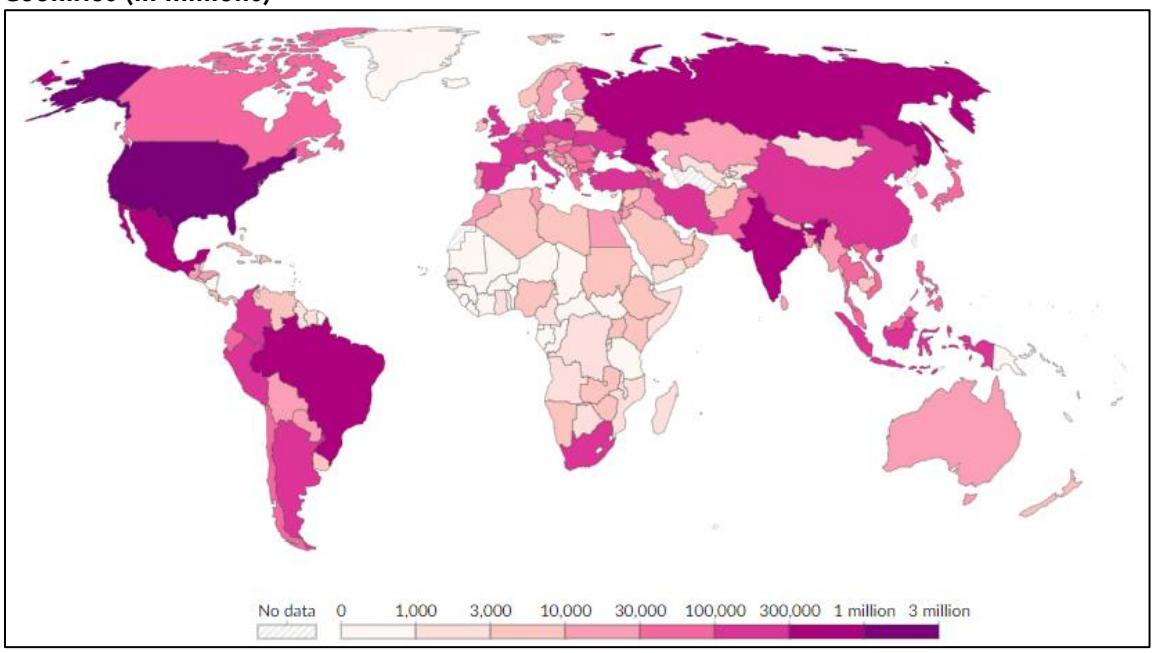


Source: WHO COVID-19 Dashboard.

2.3: DEATHS DUE TO COVID-19

Globally, 7 million deaths were reported by October 25, 2023. Map 3 presents how cumulative confirmed COVID-19 deaths are distributed globally. Due to varying protocols and challenges in the attribution of the cause of death, the number of confirmed deaths may not accurately represent the true number of deaths caused by COVID-19.

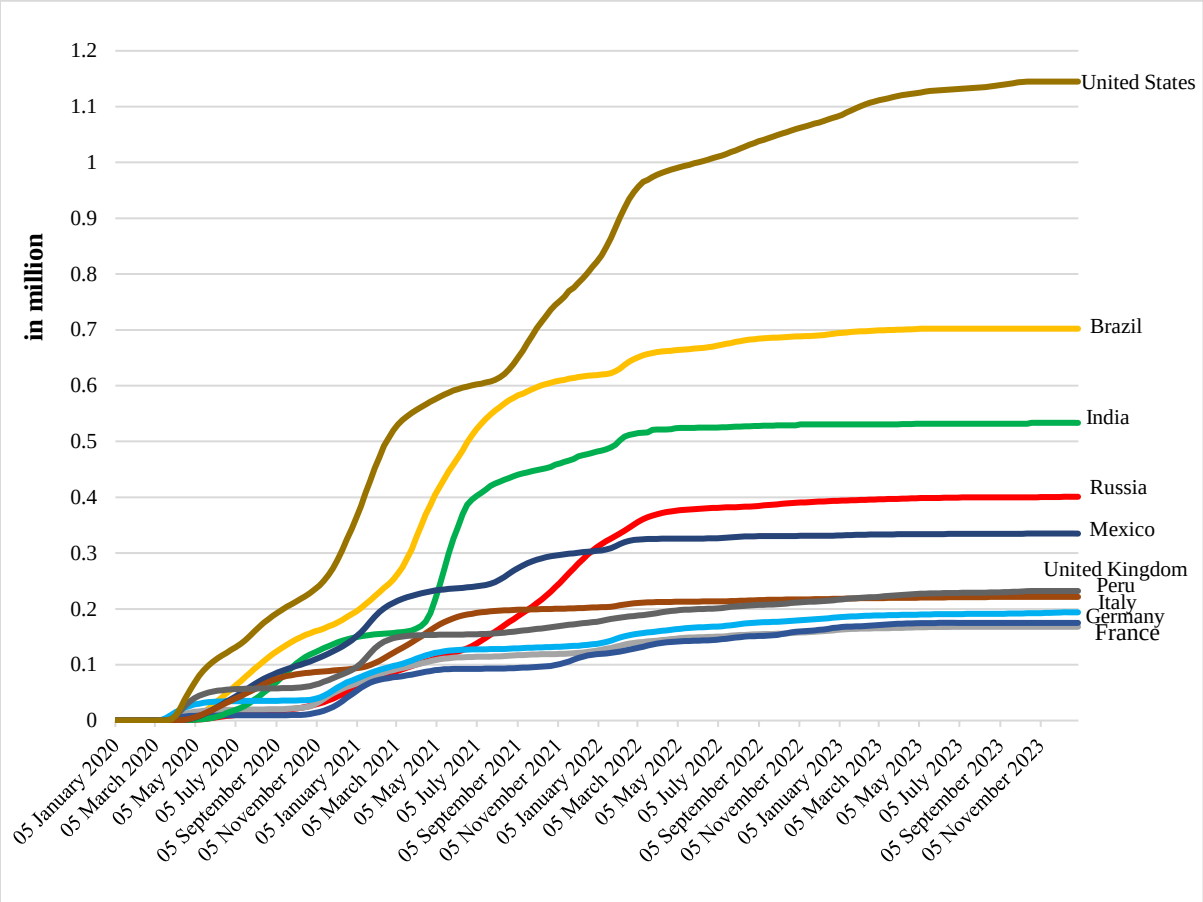
Map 3: Cumulative Confirmed COVID-19 Deaths (January 5, 2020–-December 31, 2023) across Countries (in millions)



Source: WHO COVID-19 Dashboard.

Among a total of 7 million deaths reported globally due to COVID-19, the top 10 countries contributed 60% of the deaths. The United States led the list with over 1.1 million deaths, followed by Brazil (0.7 million), India (0.53 million), Russia (0.4 million), Mexico (0.34 million), the United Kingdom (0.23 million), Peru (0.22 million), Italy (0.19 million), Germany (0.18 million), and France (0.17 million) (Figure 3).

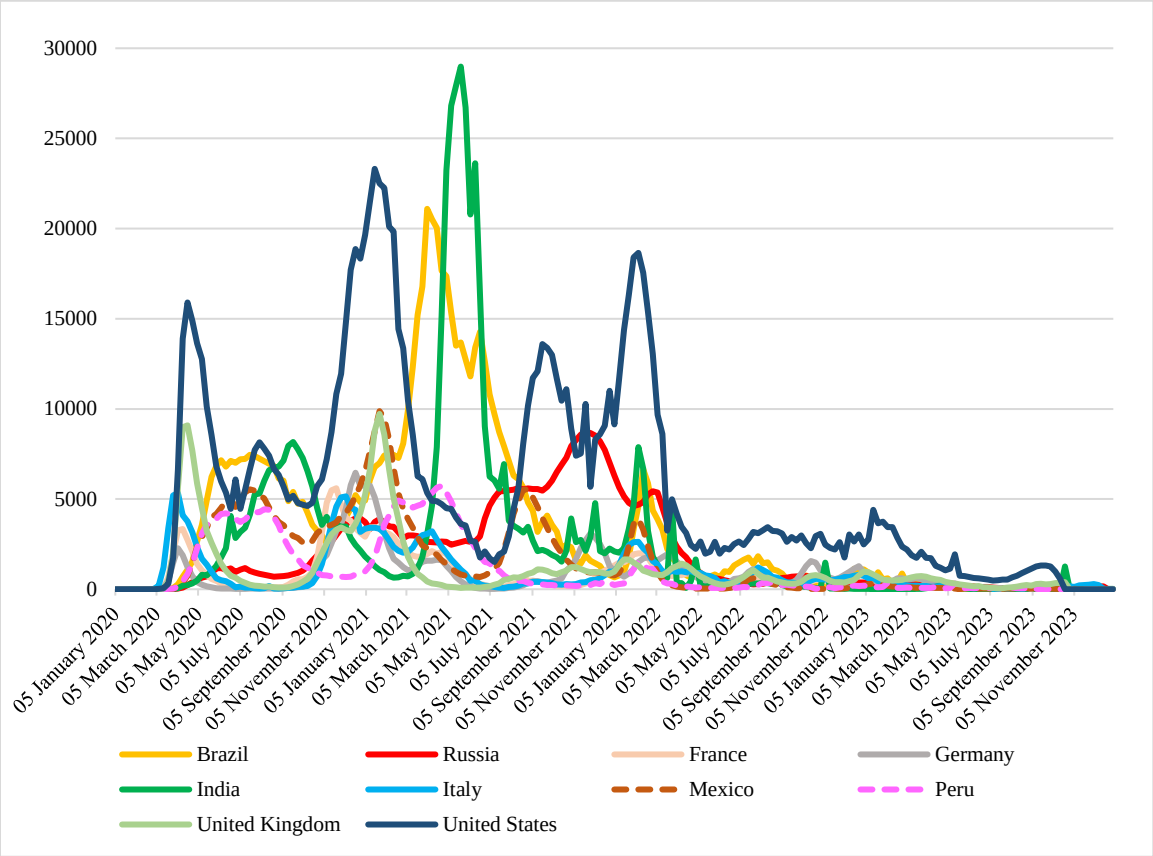
Figure 3: Cumulative Confirmed COVID-19 Deaths (January 5, 2020–December 31, 2023) in Top 10 Countries (in millions)



Source: Based on WHO COVID-19 Dashboard Data.

The highest number of COVID-19 deaths reported in the United States was after mid-January 2021, with high rates reported also in early February 2022, and after the third week of April 2020. In Brazil, its highest numbers were in April 2021, with high numbers in July 2020, and in mid-February 2022. In India, the highest number of deaths occurred at the end of May 2021, with spikes in deaths seen in mid-June 2021, after the third week of September 2020, and in early February 2022. Russia was most affected by COVID-19 deaths after the third week of November 2021, and saw increases in mid-August 2021 and early March 2022. Mexico had its highest number of deaths at the end of January 2021, and highs in August 2021 and end of July 2020. In the United Kingdom, the highest death rate was after the third week of January 2021, surpassing a previous high in mid-April 2020. Peru was most affected by COVID-19 deaths in the end of April 2021, with other peaks seen in after the third week of February 2021, the end of the second week of August 2020, and in mid-June 2020. In Italy, the highest number of deaths occurred in the first week of April 2020, following highs in early December 2020 and mid-April 2021. In Germany, the highest numbers of deaths were reported after mid-December 2020, with smaller rises seen at the end of November 2021 and before mid-April 2020. France was most affected by COVID-19 deaths around the end of November 2020, but also saw rises in death rates after the third week of January 2021 and mid-April 2020 (Figure 4).

Figure 4: Weekly Confirmed COVID-19 Deaths (January 5, 2020–December 31, 2023) in Top 10 Countries

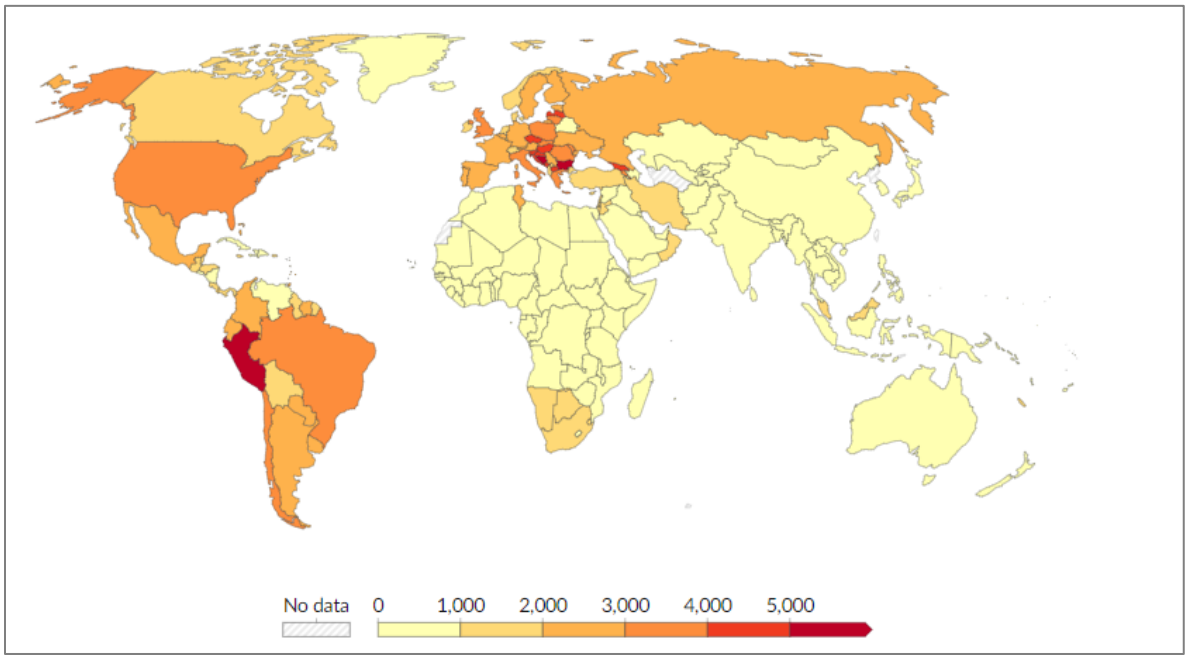


Source: Based on WHO COVID-19 Dashboard Data.

2.4: DEATHS PER MILLION POPULATION DUE TO COVID-19

Map 4 below shows how confirmed COVID-19 deaths per million population are distributed globally.

Map 4: Confirmed COVID-19 Deaths per Million Population (January 5, 2020–December 31, 2023) across Countries



Source: WHO COVID-19 Dashboard.

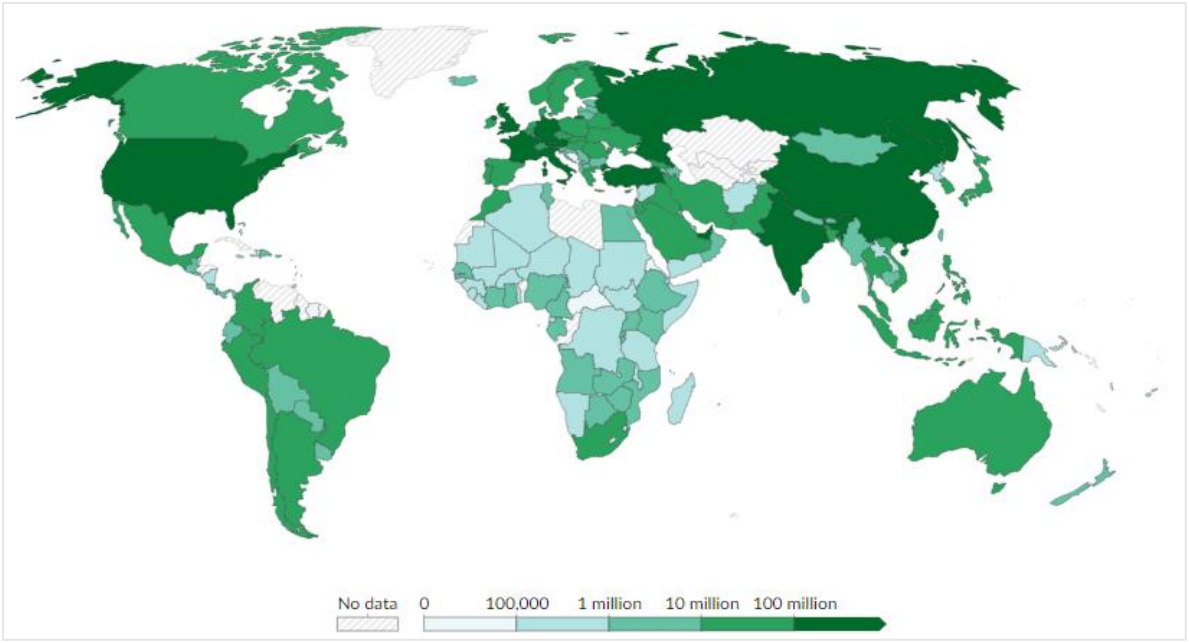
In terms of confirmed COVID-19 deaths per million population, the top 10 countries are Peru (6.5k people) followed by Bulgaria (5.6k people), Bosnia and Herzegovina (5.1 k), Hungary (4.9k), North Macedonia (4.8k), Georgia (4.6k), Croatia (4.6k), Slovenia (4.5k), Montenegro (4.2k), and Czech Republic (4.1k). Peru tops this list and is also among the top 10 countries with the most deaths from COVID-19.

Among the top 10 countries with the highest number of total COVID-19 deaths, the United Kingdom is 19th (3.4k), followed by United States (20th, 3.37k), Brazil (21st, 3.3k), Italy (22nd, 3.26k), Russia (32nd, 2.8k), Mexico (37th, 2.63k), France (38th, 2.6k), Germany (53rd, 2.1k), and India (148th, 0.38k), out of the total 224 reported countries.

2.5: TOTAL COVID-19 TESTS

Map 5 presents how COVID-19 tests were performed globally. Comparisons across countries are affected by differences in testing policies and reporting methods.

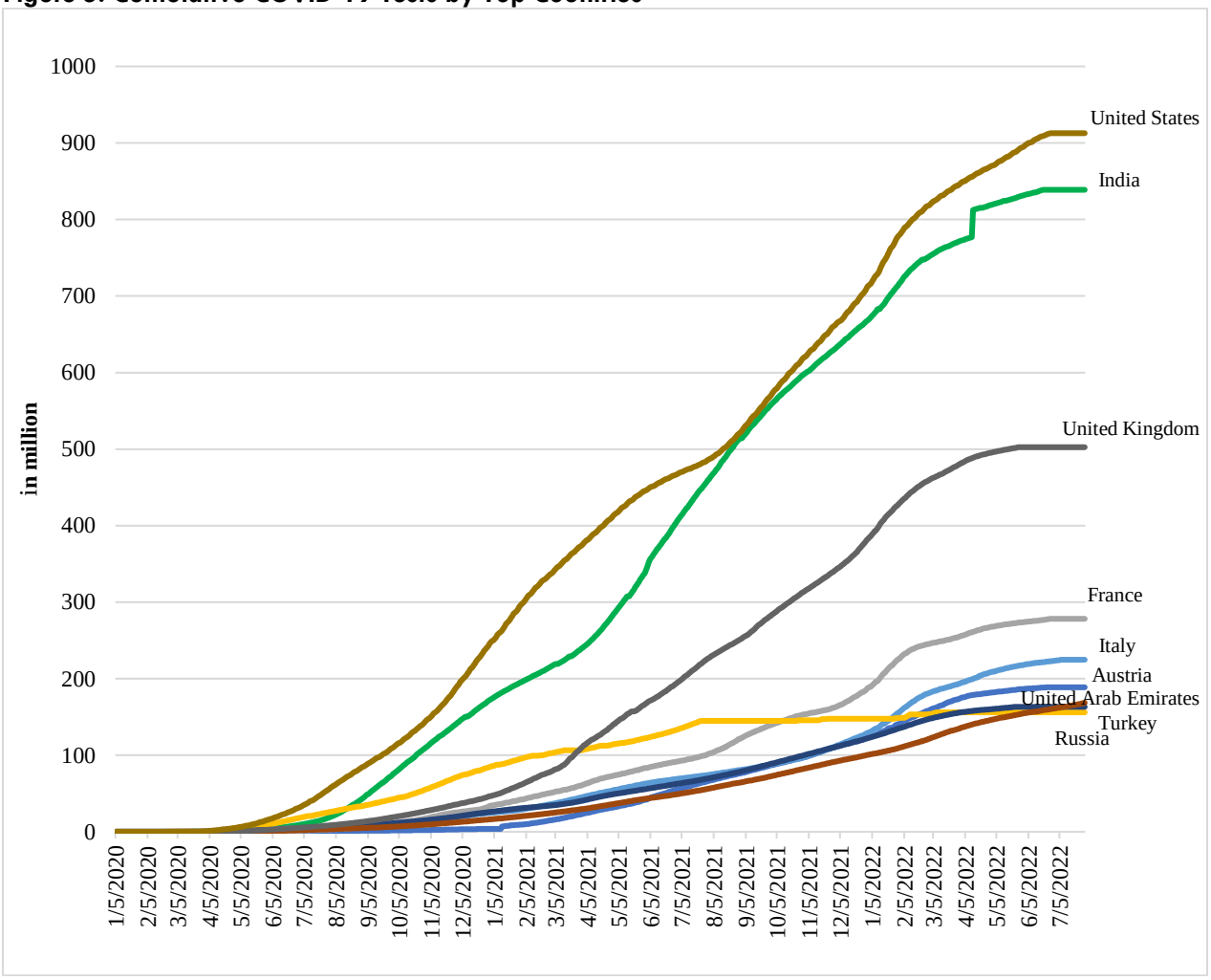
Map 5: Total COVID-19 Tests across Countries (in millions)



Note: Data is available up to June 23, 2022. Source: WHO COVID-19 Dashboard.

As per the reported data, China leads the list with 9.2 billion tests, followed by United States (913 million), India (859 million), the United Kingdom (503 million), Russia (295 million), France (278 million), Italy (225 million), Austria (190 million), the United Arab Emirates (169 million), and Turkey (163 million). Since China's time series data is not available, we presented cumulative COVID-19 tests by the remaining top 9 countries in Figure 5.

Figure 5: Cumulative COVID-19 Tests by Top Countries



Note: Data is available up to June 23, 2022. Source: Based on WHO COVID-19 Dashboard Data.

3. A Brief History of COVID-19 Vaccination: Global Efforts against a Pandemic

COVID-19 significantly impacted public health and socioeconomic well-being. In response, the scientific community embarked on an unprecedented effort to develop effective vaccines against the virus. A chronology of key milestones in the history of COVID-19 vaccination is presented in Table 1, highlighting the contributions of various countries and organizations in 2020–21.

3.1. 2022 AND BEYOND

Ongoing research and development efforts continued to improve existing vaccines, leading to the development of new formulations and addressing emerging variants. While vaccination rates vary considerably across countries, the global vaccination effort has significantly reduced COVID-19 cases, hospitalizations, and deaths. The development and deployment of COVID-19 vaccines represented a remarkable scientific achievement and a global collaborative effort. As the pandemic continues to evolve, the history of COVID-19 vaccination serves as a testament to the power of scientific innovation and international cooperation in addressing global health challenges. As research continues, new vaccines may be developed, and existing vaccines may be improved. We can learn valuable lessons from this unprecedented scientific achievement to better prepare for future pandemics.

As of October 26, 2023, the global average for full vaccination coverage was 68.7%[27]. High-income countries have achieved significantly higher coverage rates, compared to low- and middle-income countries. Within countries, disparities in access and vaccine hesitancy contribute to uneven coverage. Countries with strong health care infrastructure and resources were able to secure early access to vaccines and prioritize their populations. Further, effective communication

strategies, community engagement, and accessible vaccination sites played a crucial role in promoting vaccine uptake. Ensuring transparency, addressing misinformation, and building trust in vaccines were critical for successful rollouts. In addition, socioeconomic inequalities, access to health care, and cultural beliefs also influenced vaccination patterns. Achieving equitable distribution of vaccines remains a challenge, particularly, for vulnerable populations in low- and middle-income countries.

Vaccination significantly reduced COVID-19 transmission rates, contributing to pandemic control. Widespread vaccination led to a dramatic decline in hospitalization and death rates from COVID-19. Vaccination facilitated societal reopening and economic recovery by reducing the burden on health care systems and promoting public confidence. New variants of SARS-CoV-2 may require booster doses or adapted vaccines, posing ongoing challenges for vaccine programs. Simultaneously addressing misinformation and promoting vaccine confidence remains crucial for maximizing vaccination coverage and protecting vulnerable populations.

Table 1: Chronology of Key Milestones in the History of COVID-19 Vaccination

Timeline	Contributions
November 2020	• Pfizer and BioNTech announce positive preliminary results from their phase 3 clinical trial of the mRNA-based BNT162b2 vaccine.
December 2020	• Moderna announces positive preliminary results from its phase 3 clinical trial of the mRNA-based mRNA-1273 vaccine. • The United Kingdom becomes the first country to approve the BNT162b2 (Pfizer-BioNTech) vaccine for emergency use. • The United States grants emergency use authorization (EUA) for the Pfizer-BioNTech vaccine. • China approves its first domestically developed COVID-19 vaccine, Sinopharm BBIBP-CorV for emergency use. • The European Union approves the BNT162b2 vaccine for conditional marketing authorization. • Canada approves the BNT162b2 vaccine for emergency use. • Bahrain approves Sinopharm BIBP-CorV vaccine for emergency use. • Russia approves Sputnik V, its first COVID-19 vaccine. • Israel approves the BNT162b2 vaccine for emergency use.
January 2021	• The United Arab Emirates approves the Sinopharm BBIBP-CorV vaccine for emergency use. • India begins its vaccination program with Covishield, the Oxford-AstraZeneca vaccine manufactured by the Serum Institute of India, and COVAX developed by Bharat Biotech in collaboration with the Indian Council of Medical Research (ICMR). • Brazil commences its vaccination campaign with the CoronaVac vaccine, developed by Sinovac Biotech. • WHO approves the BNT162b2 vaccine for emergency use. In February WHO establishes the COVAX Facility to ensure equitable access to COVID-19 vaccines for developing countries.
February 2021	• United States approves the mRNA-1273 vaccine for emergency use.
March 2021	• The European Union approves the AstraZeneca vaccine for conditional marketing authorization. • WHO approves the AstraZeneca vaccine for emergency use.
April 2021	• United States approves the Johnson & Johnson (Janssen) vaccine for emergency use. In April, Moderna receives EUA for its COVID-19 vaccine in the United States and Europe.
May 2021	• WHO approves the Johnson & Johnson (Janssen) vaccine for emergency use. In this month, Johnson & Johnson's single-dose COVID-19 vaccine receives EUA in the United States.
June 2021	• WHO grants emergency use listing (EUL) to the Pfizer-BioNTech, Moderna, and AstraZeneca vaccines, paving the way for their wider distribution.
July 2021	• The COVAX initiative, led by WHO, Gavi, and the Coalition for Epidemic Preparedness Innovations (CEPI), begins delivering COVID-19 vaccines to low- and middle-income countries. • Throughout the year several additional vaccines receive approval and rollout in various countries.

4. Conclusion: Lessons Learned and the Way Forward to Building a Resilient Future beyond COVID-19

The COVID-19 pandemic has served as a stark reminder of the interconnectedness of our world and the vulnerability of our global health systems. Although the pandemic brought immense suffering and loss, it also offered valuable lessons that can guide our future preparedness and response to emerging infectious diseases.

4.1 KEY LESSONS LEARNED

Importance of Public Health Infrastructure: The pandemic exposed weaknesses in public health infrastructure worldwide, highlighting the need for investment in surveillance, early warning systems, and robust health care systems. The needs for robust and resilient health care systems equipped to handle large-scale outbreaks has become much more evident than before.

Global Cooperation and Collaboration: Effective pandemic response requires international collaboration and resource sharing. Initiatives like COVAX and global research networks demonstrated the power of cooperation in addressing global challenges. International organizations like WHO can play a crucial role in coordinating efforts and providing resources.

Science, Research, and Innovation: Rapid scientific advancements, including vaccine development, effective diagnostics, and treatments, underscored the critical role of scientific research in mitigating the impact of pandemics.

Importance of Communication and Trust: Effective communication and building public trust in science and health authorities are crucial for successful pandemic response and vaccination campaigns. Anti-vaccine movements played a critical role in increasing the number of unnecessary deaths, including in developed countries such as the United States. Therefore, creating trust in science and technology through effective communication and information is critical.

Equity and Access: The pandemic exposed the inequities in access to health care and resources around the world. Addressing these inequities is essential for building a more resilient and equitable global health system.

4.2 THE WAY FORWARD

Building upon the lessons learned, we must now focus on strengthening our global health architecture and component parts of national health systems for improving preparedness for future pandemics. This includes:

Strengthening Global Health Governance: Empowering organizations like WHO to facilitate international cooperation and resource sharing.

Investing in Public Health Infrastructure: Strengthening public health systems, including surveillance, early warning systems, and health care capacity, is essential for early detection and rapid response to outbreaks.

Promoting Global Collaboration: Fostering international cooperation and coordination in research, vaccine development, and resource sharing is crucial for tackling global health threats effectively.

Enhancing Scientific Research and Development: Continued investment in scientific research, including pandemic preparedness and response research, is essential for developing innovative solutions to emerging health challenges.

Building Trust and Addressing Misinformation: Effective communication strategies, public engagement, and tackling misinformation are crucial for building trust in science and public health institutions.

Prioritizing Global Health Equity: Ensuring equitable access to health care, vaccines, and other essential resources for all populations, regardless of their origin or socioeconomic status, is vital for a sustainable global health response.

By learning from the COVID-19 pandemic and taking decisive action, we can build a more resilient and equitable future, and be prepared to face the health challenges of tomorrow. We must act collectively and with urgency to ensure that no one is left behind, and that we are better equipped to prevent and respond to future pandemics.

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References

1. Baum, H. Compiler. The great pandemics of history. University of Cincinnati. https://www.uc.edu/content/dam/refresh/cont-ed-62/olli/s21/history-of-pandemics.pdf
2. Higgins-Dunn, N. Bill Gates: Coronavirus may be 'once-in-a-century pathogen we've been worried about'. CNBC Health and Science 2020 February 28. https://www.cnbc.com/2020/02/28/bill-gates-says-coronavirus-may-be-once-in-a-century-pathogen.html
3. Gates, Bill. Responding to Covid-19 – A-Once-in-a-Century Pandemic? *N Engl J Med* 2020;382(18):1677-1689. doi: 10.1056/NEJMp2003762.
4. Gates, Bill. The next outbreak? We're not ready. TED2015. https://www.ted.com/talks/bill_gates_the_next_outbreak_we_re_not_ready?language=en
5. Larnaud, Natacha. Bill Gates warned of a deadly pandemic for years—and said we wouldn't be ready to handle it. CBS News 2020 March 19. https://www.cbsnews.com/news/coronavirus-bill-gates-epidemic-warning-readiness/
6. Munich Security Conference Panel Discussion. Get Well Soon: Finding a Way Out of the Pandemic. 2022 February 18. https://securityconference.org/en/msc-2022/agenda/event/get-well-soon-finding-a-way-out-of-the-pandemic/
7. Cutler DM, Summers LH. The COVID-19 pandemic and the $16 trillion virus. JAMA. 2020;324(15):1495-1496.
8. Velavan TP, Meyer CG. The COVID-19 epidemic. Trop Med Int Health 2020;25:278-280.
9. Fehr AR, Perlman S. Coronaviruses: an overview of their replication and pathogenesis. Methods Mol Biol. 2015;1282:1-23.
10. Lu R, Zhao X, Li J, Niu P, Yang B, Wu H, et al. Genomic characterization and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 2020;395:565-574.
11. Cascella M, Rajnik M, Cuomo A, Dulebohn SC, Napoli RD. *Features, Evaluation and Treatment Coronavirus (COVID-19)*. Treasure Island, FL: Stat Pearls Publishing; 2020.
12. Woo PCY, Lau SKP, Lam CSF, Lau CCY, Tsang AKL, Lau JHN, et al. Discovery of seven novel mammalian and avian coronaviruses in the genus delta coronavirus supports bat coronaviruses as the gene source of alphacoronavirus and beta coronavirus and avian coronaviruses as the gene source of gamma coronavirus and delta coronavirus. J Med Virol. 2012;86:3995-4008.
13. Tyrrell DA, Bynoe ML. Cultivation of viruses from a high proportion of patients with colds. Lancet 1966;176-177.
14. Korber B, Fischer WM, Gnanakaran S, Yoon H, Theiler J, Abfalterer W, et al. Tracking changes in SARS-CoV-2 spike: evidence that D614G increases infectivity of the COVID-19 virus. Cell 2020;182:812-827.e19.
15. Guo YR, Cao QD, Hong ZS, Tan YY, Chen SD, Jin HJ, et al. The origin, transmission and clinical therapies on coronavirus disease 2019 (COVID-19) outbreak an update on the status. Mil Med. 2020;7:1-10.
16. Hoffmann M, Kleine-Weber H, Krüger N, Müller M, Drosten C, Pohlmann S, et al. The novel coronavirus 2019 (2019-nCoV) uses the SARS-coronavirus receptor ACE2 and the cellular protease TMPRSS2 for entry into target cells. Biorxiv.2020; doi:10.1101/2020.01.31.929042.
17. Sola I, Almazan F, Zuniga S, Enjuanes L. Continuous and discontinuous RNA synthesis in coronaviruses. Annu Rev Virol. 2015;2:265-268.
18. Galloway SE, Paul P, MacCannell DR, Johansson MA, Brooks JT, MacNeil A. et al. Emergence of SARS-CoV-2 B117 lineage – United States. MMWR Morb Mortal Wkly Rep. 2021;70:95-99.
19. Volz E, Mishra S, Chand M, Barrett JC, Johnson R, Geidelberg L. et al. Assessing transmissibility of SARS-CoV-2 lineage B117 in England. Nature 2021;593:266-269.
20. Cerutti G et al. Increased resistance of SARS-CoV-2 variant P.1 to antibody neutralization. bioRxiv. 2021;29:747-751.e4.
21. Tegally H, Wilkinson E, Giovanetti M, Iranzadeh A, Fonseca V, Giandhari J, et al. Detection of a SARS-CoV-2 variant of concern in South Africa. Nature 2021;592:438-443.
22. Faria NR, Mellan TA, Whittaker C, Claro IM, Candido DDS, Mishra S. et al. Genomics and epidemiology of a novel SARS-CoV-2 lineage in Manaus, Brazil. medRxiv 2021.doi:10.1126/science.abh2644.
23. WHO. Enhancing response to Omicron SARS-CoV-2 variant. 2021. https://www.who.int/news/item/28-11-2021-update-on-omicron.
24. Sankaran V. First image of omicron coronavirus variant shows many more mutations in area that interacts with human cells. Independent 2021 Nov 29. https://www.independent.co.uk/news/science

/omicron-covid-variant-mutations-image-b1965780.html

25. Zhang W, Davis BD, Chen SS, Sincuir Martinez JM, Plummer JT, Vail E. Emergence of a novel SARS-CoV-2 variant in Southern California. JAMA 2021;325:1324-1326.
26. The EU's covid-19 recovery fund has changed how Europe spends money. The Economist 2022 May https://www.economist.com/europe/2022/05/26/the-eus-covid-19-recovery-fund-has-changed-how-europe-spends-money?utm_medium=email.internal-newsletter.np&utm_source=salesforce-marketing-cloud&utm_campaign=espresso.US&utm_content=-the-eu-s-scramble-to-find-new-money-2023-12-08&utm_term=12/08/23
27. WHO COVID-19 Dashboard Data. https://data.who.int/dashboards/covid19/data?n=c.