Global South Healthcare Journal
www.gshealthjournal.com

ORIGINAL RESEARCH
Published : 27 January 2025

Global Public Health Emergencies: Insights for Future Preparedness based on India's Response to the COVID-19 Pandemic

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ABSTRACT

The COVID-19 pandemic posed unprecedented challenges to India, testing its healthcare system, economy, and social structures. Early interventions, such as the stringent nationwide lockdown, significantly mitigated the virus's spread and saved lives. India's rapid scaling of healthcare infrastructure, aggressive testing, and vaccine development, including Covishield and Covaxin, were pivotal in managing the crisis. Despite successes, systemic challenges such as underfunded healthcare and supply chain vulnerabilities were exposed.

India administered over 2.2 billion vaccine doses and supported global health through the Vaccine Maitri initiative, providing vaccines to over 95 countries. Community-based innovations, decentralized responses, and technology-driven measures like Aarogya Setu and telemedicine emerged as vital strategies. However, the pandemic underscored the need for enhanced public health spending, equitable access, and robust surveillance systems.

Lessons from India's response highlight the importance of preparedness, leveraging digital health solutions, and addressing long-term impacts such as long COVID. Strengthening public health infrastructure, fostering public-private partnerships, and investing in research are critical for future resilience. India's global leadership in pharmaceutical manufacturing and its initiatives, such as *Aatmanirbhar Bharat*, position it to contribute significantly to global health security under the '*One World One Health*' framework.

Global South Healthcare Journal, 2025; 1(1).

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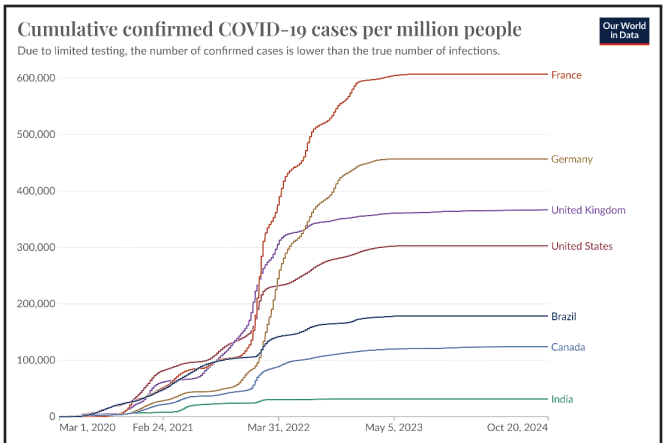
KEYWORDS:
Aatmanirbhar Bharat, COVID-19, Covishield, Covaxin, Healthcare management, Health Policy, Pandemic, Public Health, Vaccine Maitri

HOW TO CITE:
Prasad U. Global Public Health Emergencies: Insights for Future Preparedness based on India's Response to the COVID-19 Pandemic. Global South Healthc J. 2025;1(1):7–16

INTRODUCTION

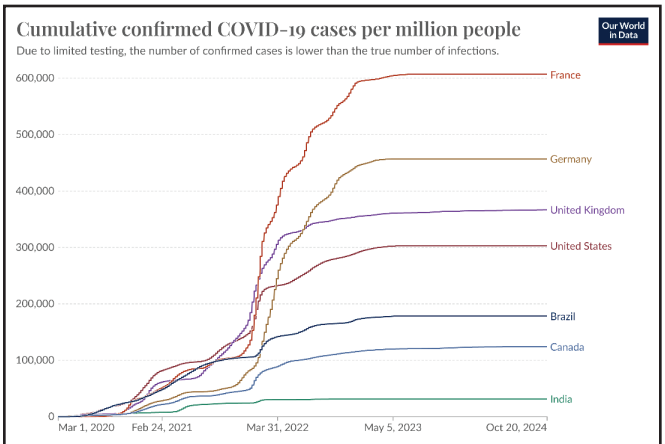
The COVID-19 pandemic has emerged as an unparalleled global health crisis, significantly impacting nations' healthcare systems, economies, and social frameworks.[1] India, with its vast population and diverse socio-economic landscape, faced unique challenges in managing the pandemic. Despite the immense strain on its healthcare system, India demonstrated a lower number of cases and deaths per million compared to several developed countries.[2] As of October 20, 2024, India recorded 31,600 COVID-19 cases per million people (Figure 1) which is significantly lower than the United States (302,860), Brazil (178,368), and the United Kingdom (366,781).[3] India also recorded 374 deaths per million (Figure 2), notably fewer than the United States, Brazil, and the United Kingdom.[3] These figures underline both the successes and areas for improvement in India's pandemic response.

India's pandemic experience was marked by distinct phases. The first wave in early 2020 prompted a nationwide lockdown, an early intervention aimed at mitigating the virus's spread.[4] However, the second wave in early 2021, driven by the highly contagious Delta variant, overwhelmed hospitals and exposed critical shortages in medical supplies such as oxygen and hospital beds.[5] The healthcare system



Source: *World Health Organization (2024), population, based on various sources (2024) -- Our World in Data*

Figure 1: Cumulative confirmed COVID-19 cases per million people across selected countries (March 2020 – October 2024).



Source: *World Health Organization (2024), population based on various sources (2024) -- major processing by Our World in Data*

Figure 2: Cumulative confirmed COVID-19 deaths per million people across selected countries (March 2020 – October 2024).

faced unprecedented pressure, despite efforts from the government, non-governmental organizations, and local communities to alleviate the crisis. The third wave, though less severe, highlighted the persistent threat of emerging variants like Omicron, underscoring the evolving nature of the pandemic.[6]

Here, we discuss India's COVID-19 pandemic management, examining its challenges, successes, and lessons learned. By understanding the strategies employed and their outcomes, the study seeks to offer insights for improving pandemic preparedness and response in the future. These reflections will contribute to developing a more resilient healthcare system, ensuring better preparedness for public health crises, and fostering a proactive approach to managing pandemics in an interconnected world.

ABOUT THE COVID-19 PANDEMIC

Coronavirus disease 2019 (COVID-19) is a respiratory illness caused by the novel coronavirus SARS-CoV-2, initially identified in Wuhan, China, in December 2019.[7] Genetic analysis reveals that SARS-CoV-2 is closely related to the SARS virus, with the outbreak being traced to a seafood market in Wuhan.[8]

The pandemic expanded at a rapid pace globally. The first 100,000 cases were reported within 67 days, while the subsequent 100,000 cases were documented in progressively shorter intervals of 11, 4, and 2 days.[9] In response, the World Health Organization (WHO) issued a travel advisory on January 27, 2020, declared a public health emergency on January 30, and designated COVID-19 as a pandemic on March 11, 2020.[10]

In India, SARS-CoV-2 is categorized as a non-indigenous "Immigrant Virus," brought in by travellers arriving from affected countries. India's first three cases were reported on January 30, February 2, and February 3, 2020, all linked to Wuhan. By March 2020, COVID-19 cases began appearing across all Indian states.[11]

Approximately 75% of COVID-19 patients in India were asymptomatic or pre-symptomatic, while 5% experienced mild illness (Figure 3). Around 15% displayed moderate symptoms, and nearly 5% of patients required intensive care unit (ICU) hospitalization due to severe symptoms. Among those admitted to the ICU, approximately 1% necessitated ventilator support.[12]

As depicted in Figure 4, while most COVID-19 cases occurred in individuals below 50, the majority of fatalities were recorded in those aged 50 or older. The table on the left categorizes cases and deaths into seven age groups, highlighting a stark contrast in mortality rates. For instance, individuals aged 0 to 9 years represented only 1% of cases and deaths, while those aged 21 to 30 accounted for 23% of cases but just 3% of deaths. Mortality rates rose sharply in those over 50, with the 51 to 60 group making up 14% of cases but 31% of deaths, and those above 60 comprising 12% of

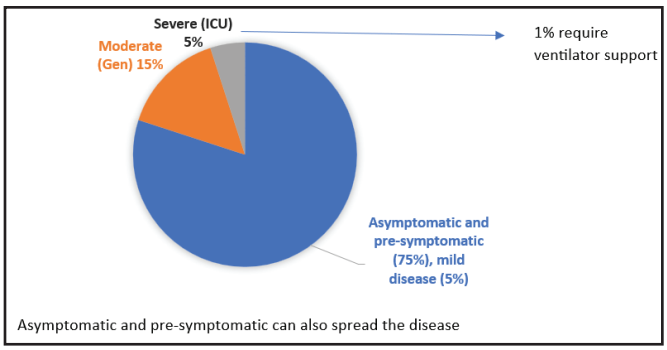
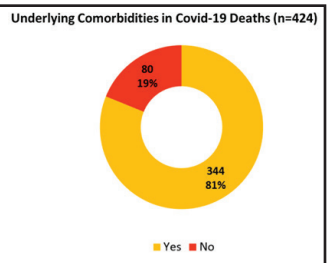


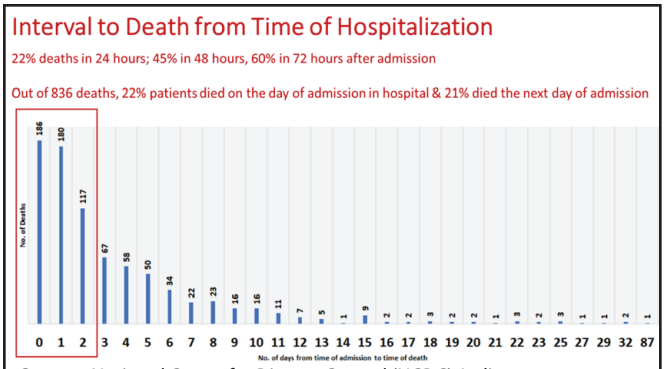
Figure 3: Clinical characteristics of COVID-19 infection in India.

Age (years)	Cases %	Deaths %
0-9	1	1
10-20	10	0
21-30	23	3
31-40	21	7
41-50	17	18
51-60	14	31
>60	12	40



Source: *National Centre for Disease Control (NCDC), India*

Figure 4: Distribution of COVID-19 cases and deaths by age; role of comorbidities



Source: *National Centre for Disease Control (NCDC), India*

Figure 5: Analysis of the time interval between hospital admission and fatalities during the early phases of the COVID-19 pandemic in India

cases yet 40% of deaths. Around 81% of 424 analysed deaths-involved comorbidities, such as diabetes and chronic kidney disease, while only 19% occurred in those without underlying conditions.[13] This underscores the heightened vulnerability of older adults and individuals with pre-existing health issues, emphasizing the need for targeted interventions to protect high-risk groups.

An analysis of the time interval between hospital admission and death during the early months of the pandemic (Figure 5) revealed that 22% of the 836 deaths occurred on the day of admission, and 21% of the patients died the next day. In total, 45% of fatalities occurred within 48 hours, and 60% within 72 hours, underscoring the urgency of timely medical care.[13] The sharp decline in deaths after the third day highlights that many high-risk patients sought care too late, reducing their survival chances. Beyond one week, fatalities were significantly lower, emphasizing the need for early diagnosis and intervention to improve outcomes.

INDIA'S COVID-19 PANDEMIC RESPONSE

India's nationwide lockdown, from March 25 to May 31, 2020, remains one of the most stringent measures undertaken globally, with a Stringency Index score of 100. Implemented at an early stage, when daily cases were just 0.04 per million population and there were zero deaths per million population, this lockdown aimed to pre-emptively curb the spread of COVID-19. In contrast, countries like Italy imposed a lockdown with a Stringency Index of 93.25 only after daily cases had risen to 79 and deaths to 12 per million population (Table 1). Six months into the pandemic, India reported 1.6 million cases and 35,000 deaths -- a comparatively lower toll than Europe and North America, where advanced healthcare systems struggled against 8.2 million cases and over 418,000 deaths.

Table 1: India's lockdown stringency compared with other nations on 25 March 2020

	Stringency Index	Daily Covid-19 Cases Per Milion Population	Daily Covid-19 Death Per Million Population
India	**100**	**0.04**	**0**
Italy	93.25	79.21	12.29
France	89.41	58.80	3.68
Spain	77.64	96.61	10.99
United Kingdom	75.13	14.24	2.19
United States	68.41	33.95	0.65
Iran	54.23	16.80	1.45

Source: *Derived from data at https://ourworldindata.org/grapher/covid-stringency-index?year=2020-05-08*

The Indian government believed the outbreak was largely contained in specific regions, contributing to one of the lowest disease burdens globally, largely due to the lockdown measures. Active COVID-19 cases and deaths were fairly concentrated in India in early July, 2020. (Table 2).

Table 2: Geographic distribution of COVID-19 cases and deaths in India (early July 2020).

72% Active Case 5 Sates	82% Deaths in 5 States	66% Active Cases in 15 Cities/ Districts	76% Deaths in 15 Cities/ Districts
Maharashtra	Maharashtra	Thane	Mumbai
Tamil Nadu	Delhi	Delhi	Delhi
Delhi	Gujarat	Mumbai	Ahamedabad
Karnataka	Tamil Nadu	Chennai	Thane
Telangana	Uttar Pradesh	Hyderabad	Chennai
		Pune	Pune
		Bengaluru Urban	Kolkata
		Palghar	Solapur
		Aurangabad	Aurangabad
		Chengalpattu	Jalgaon
		Kamrup	Indore
		Metropolitan	Nashik
		Raigad	Surat
		Madurai	Jaipur
		Kolkata	Bengaluru Urban

Hindsight suggests that this decision likely prevented a catastrophic outbreak. For instance, as of June 11, 2020, India's reported deaths per million stood at just six, far lower than the UK's 620, Spain's 581, and Italy's 565.[14] A centre citing statistical models estimated that the lockdown might have averted 1.4 to 2.9 million cases in India, saving 37,000 to 78,000 lives.[15] This impact aligns with global findings, where restrictions in 11 European nations reportedly prevented over 3 million deaths.

HEALTH INFRASTRUCTURE IMPROVEMENTS

The lockdown period served as a critical window for strengthening India's healthcare infrastructure. COVID-19 care centers, ICU facilities, and isolation wards were rapidly established to accommodate the surge in cases. Testing capacity saw remarkable growth, with over 2,000 laboratories operational nationwide by mid-2020.[16] This scaling-up enabled aggressive testing and contact tracing strategies, which became crucial as restrictions eased. The establishment of these facilities not only addressed immediate needs but also created a foundation for long-term improvements in healthcare delivery.

Vaccine Development and Rollout

India's vaccine development and rollout were notable achievements stemming from the lockdown period. Collaborative efforts with the private sector led to the rapid development of vaccines like Covishield and Covaxin, which formed the backbone of India's vaccination campaign.[2,17] These efforts underscored the importance of public-private partnerships in addressing health crises. The development of indigenous vaccines further strengthened India's capacity to manage future waves of infection and reduce transmission rates, making it a pivotal aspect of the country's long-term COVID-19 strategy.

Testing and Surveillance Strategies

The lockdown period also facilitated a robust expansion of testing and surveillance mechanisms. With over 2,000 operational laboratories by mid-2020, India ramped up its testing capabilities to aggressively identify and isolate cases. Enhanced contact tracing complemented these efforts, ensuring a systematic approach to mitigating virus transmission. The integration of testing and surveillance strategies into the public health system helped India manage the pandemic even as restrictions eased.

Economic and Social Impact

Despite its successes, the lockdown imposed significant economic and social costs, disproportionately affecting vulnerable populations, especially migrant workers. The government acknowledged these hardships and transitioned to a more decentralized approach, granting states greater flexibility in implementing containment measures. Districts were classified into red, orange, green, and containment zones, allowing for region-specific relaxations while maintaining vigilance in hotspots.

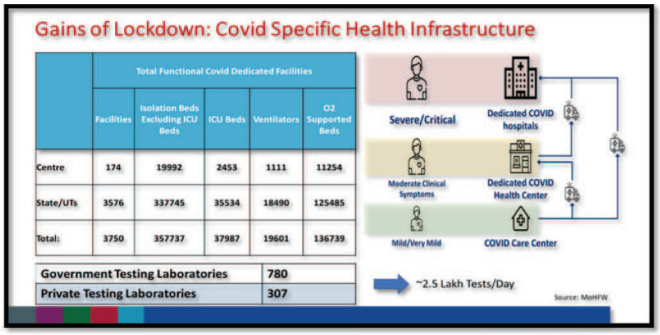


Figure 6A: COVID-specific health infrastructure details reported by MoHFW
Source: *Ministry of Health and Family Welfare, India*

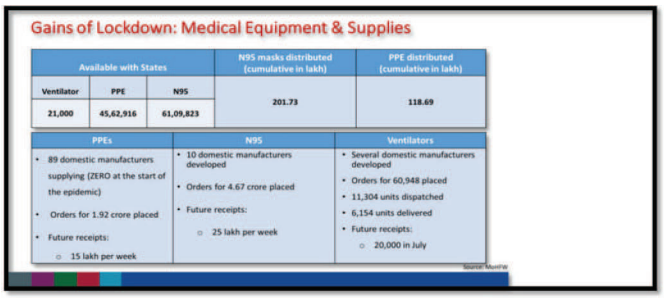


Figure 6B: Medical equipment and supplies improvements reported by MoHFW
Source: *Ministry of Health and Family Welfare, India*

Balancing Immediate Gains and Long-Term Challenges

While the strictness of the initial lockdown remains a subject of debate, it undoubtedly mitigated the immediate impact of the pandemic. Comparisons to severely affected regions like New York and Lombardy highlight the potential scale of losses that India's proactive measures likely prevented. At the same time, the lockdown exposed systemic challenges, such as an underfunded healthcare system and supply chain vulnerabilities, which remain critical areas for future improvements.[18] Strengthening healthcare infrastructure, continuing vaccine research, and addressing economic inequalities are essential steps as India moves forward from the pandemic.

HEALTH SYSTEM PREPAREDNESS

During the lockdown, initiatives were launched to strengthen

healthcare capacity, including building COVID-19 specific hospitals, training healthcare workers, and designating testing laboratories (Figure 6A). These efforts also focused on increasing hospital beds and ventilators, as well as providing personal protective equipment (PPE) for healthcare workers (Figure 6B). Recognizing the need for a sustained response early in the pandemic, these measures were instrumental in reducing mortality rates and managing healthcare demand effectively.

By May 10, 2020, 7,740 facilities across 483 districts were designated for COVID-19 care, offering 656,769 isolation beds, 305,567 beds for confirmed cases, 351,204 for suspected cases, 99,492 oxygen-supported beds, and 34,076 ICU beds.[19] The PM CARES Fund allocated INR 2000 crore to procure 50,000 ventilators for government COVID-19 hospitals.[20]

Providing PPE for healthcare workers was critical in preventing nosocomial infections and maintaining morale, as infections among healthcare workers could transform them into "super-spreaders". Ensuring adequate supplies of PPE and deploying alternative teams were essential to mitigate risks from fatigue, exposure, and quarantine requirements.

Treatment strategies were differentiated for mild and severe COVID-19 cases (Figure 7).[21] Many infected individuals were asymptomatic, while symptomatic patients often experienced mild conditions manageable at home with modified physical distancing. Government guidelines emphasized reserving hospital admissions for cases needing specialized care, ensuring ICUs had trained professionals equipped with protective gear. A steady oxygen supply in ICUs was a priority, while home isolation was encouraged for asymptomatic or mildly symptomatic individuals. COVID-19 hospitals and health centres catered to patients based on disease severity. India's low case fatality rate reflected

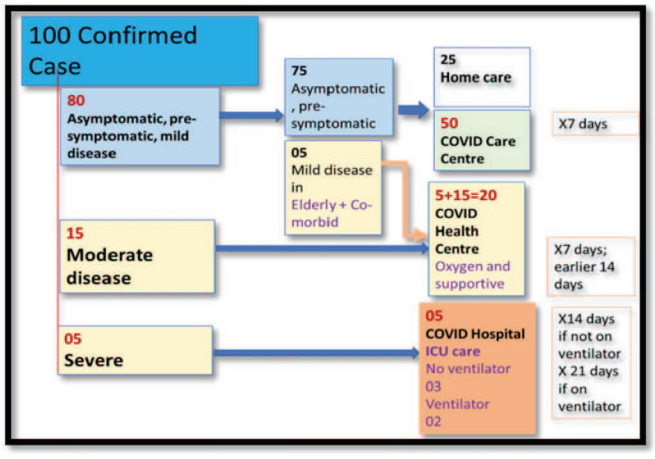


Figure 7: Differentiated treatment strategies for mild and severe COVID-19 cases.

Source: *Directorate of Health Services, India.*

the clinical management experience gained during the preparatory stages.

Physical distancing measures were essential to reduce virus spread, while programs promoting social connections helped address mental health challenges from anxiety and lockdowns.[22] Stigma and discrimination affected specific groups, including certain religious communities and returning migrants, even after quarantine. The government worked with media and local organizations to educate the public on these issues.

The lockdown also brought increased awareness about personal hygiene practices, including widespread mask usage, hand hygiene, and cough etiquette. Public and private initiatives aimed at reducing stigma and discrimination were essential for managing mental health and social challenges.

Surveillance

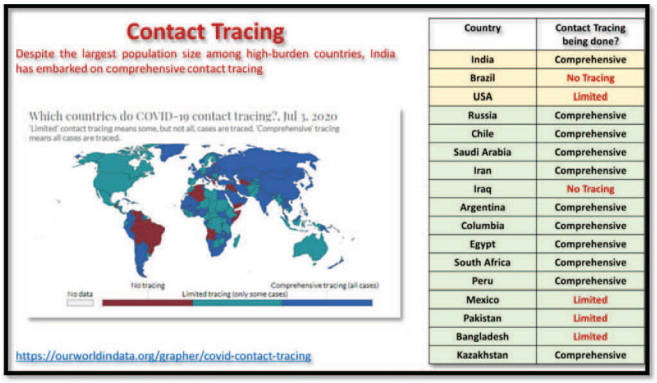
A robust surveillance mechanism for Influenza-like Illnesses (ILI) and Severe Acute Respiratory Illness (SARI) involved Accredited Social Health Activists (ASHAs), Auxiliary Nurse Midwives (ANMs), and Multi-Purpose Workers (MPWs), along with clinical facilities, including private hospitals. Emphasis was placed on daily reporting to identify geographic and temporal clusters of cases, with support from trained epidemiologists. MoHFW and the Indian Council of Medical Research (ICMR) conducted a community-based serological survey to estimate SARS-CoV-2 prevalence among 24,000 adults across 69 districts in 21 states.[23]

Tracing, Testing and Diagnostics

To strengthen contact tracing strategies (Figure 8), the *Aarogya Setu* app was launched, enabling users to assess infection risk based on location and interactions. By mid-May 2020, the app had been downloaded over 100 million times, alerting approximately 140,000 users of potential exposure.[24]

Testing infrastructure expanded from 14 laboratories in February, 2020 to 106 Virus Research & Diagnostic Laboratories (VRDLs) by March-end. Daily testing capacity grew from 700 tests in early March to around 250,000 by mid-July, 2020 .[25] The testing strategy included both RT-PCR tests, the gold standard for accuracy, and rapid antigen tests for quicker results.

This dual approach effectively met the need for both precision and speed, especially in densely populated areas and during outbreaks, with rapid tests being particularly useful in high-traffic locations like airports and railway stations. Ensuring fair access to testing in urban and rural areas was crucial. To address inequalities, mobile testing units and home testing kits were introduced. Mobile units effectively reached isolated communities, reducing travel for testing, while home kits provided privacy and comfort. Digital tools for monitoring and reporting improved testing



Country	Contact Tracing being done?
India	Comprehensive
Brazil	No Tracing
USA	Limited
Russia	Comprehensive
Chile	Comprehensive
Saudi Arabia	Comprehensive
Iran	Comprehensive
Iraq	No Tracing
Argentina	Comprehensive
Columbia	Comprehensive
Egypt	Comprehensive
South Africa	Comprehensive
Peru	Comprehensive
Mexico	Limited
Pakistan	Limited
Bangladesh	Limited
Kazakhstan	Comprehensive

Figure 8: COVID-19 contact tracing strategies across various countries as of July 3, 2020.

Source: *Our World in Data tracker.*

efficiency, allowing individuals to schedule tests and receive results through apps and online platforms.

Non-COVID Health Services

The resumption of routine health services was deemed essential, leading to the urgent reinstatement of primary, secondary, and tertiary care with necessary precautions for healthcare personnel. The central government collaborated with state governments to maintain routine immunization, antenatal check-ups, and other vital services during the lockdown. Guidance documents were issued, including one on reproductive and maternal health services during and after the COVID-19 pandemic.

Telemedicine Adoption

The pandemic accelerated the adoption of telemedicine, with the release of the Telemedicine Practice Guidelines by MoHFW and NITI Aayog in March, 2020 (Figure 9). This facilitated access to medical advice through services like e-Sanjeevani and e-Sanjeevani OPD, which conducted over 1 million tele-consultations across 550 districts by December, 2020.

COVID-19 Vaccination

India has administered over 2.2 billion COVID-19 vaccine doses to eligible individuals, focusing on high-risk groups and frontline workers.[26] Introducing booster doses and new vaccines for emerging variants has strengthened the country's defence against the virus, significantly reducing severe cases and hospitalizations. To address vaccination campaign challenges, decisive policy measures were implemented under the Prime Minister's leadership, including domestic vaccine production, stringent clinical trial processes for safety, and training healthcare personnel for careful distribution.

India's COVID-19 vaccination program launched on January 16, 2021, initially targeting healthcare and frontline workers, later expanding to senior citizens, those with underlying health conditions, and all adults. The central government managed vaccine procurement and distribution at no cost to states. The primary vaccines were Covishield, developed by AstraZeneca and manufactured by the Serum Institute of India, and Covaxin, developed by Bharat Biotech. By October 2021, India had delivered over 1 billion doses, marking a significant milestone in the fight against COVID-19.[27]

Vaccine Maitri

The Vaccine Maitri initiative, meaning 'Vaccine Friendship',

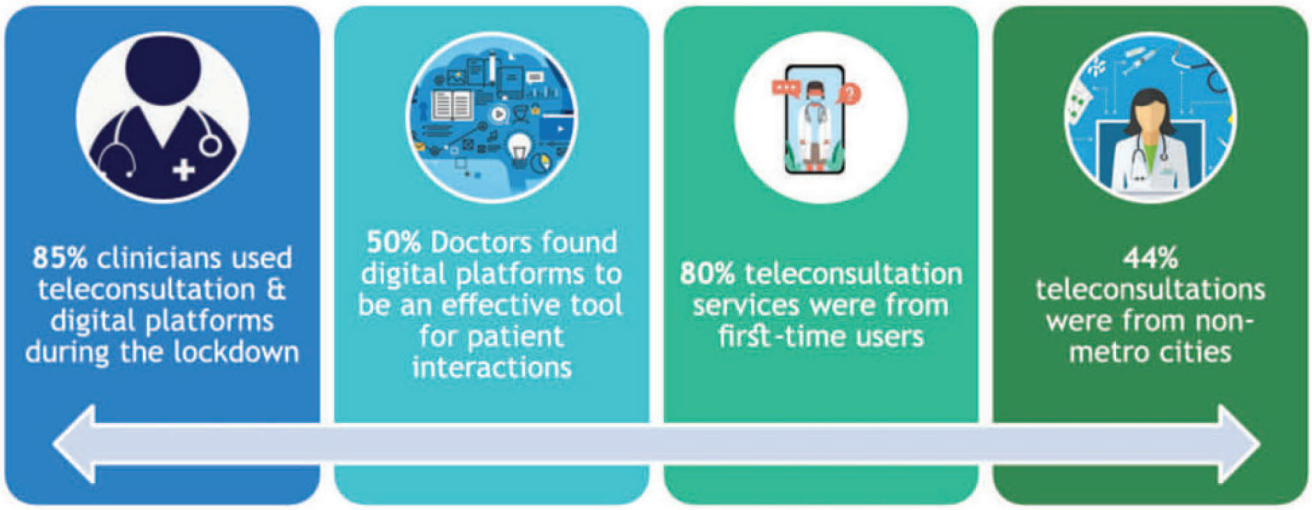


Figure 9: Transition to digital healthcare during March 1–May 31, 2020

Source: *Insights from a Boston Consulting Group survey*

was launched by the Indian government on January 20, 2021, to support the international distribution of COVID-19 vaccines. Inspired by the principle of '*Vasudhaiva Kutumbakam*' ('The World is One Family'), it reflects India's commitment to global solidarity[28]. India supplied vaccines to over 95 countries, including neighbouring nations and low-income states, via donations and commercial sales, with millions of doses delivered through the COVAX facility. Despite facing its own COVID-19 challenges, India resumed vaccine exports in October 2021, highlighting its crucial role in global health.[29]

This initiative served as both a diplomatic tool and a showcase of India's pharmaceutical capabilities, earning recognition from international organizations. The WHO and the United Nations commended India's efforts in supporting low- and middle-income countries in the fight against COVID-19.

Aatmanirbhar Bharat

The pandemic's impact extended beyond health, worsening food insecurity and livelihoods. The government launched several *Aatmanirbhar Bharat Abhiyaan* (Self-Reliant India) packages to improve the health sector, including Production-Linked Incentive schemes to boost domestic pharmaceutical and medical device production. To ensure food security during the pandemic, the *Pradhan Mantri Garib Kalyan* package provided free food grains to 800 million people, while the 'One Nation One Ration Card' scheme benefited 690 million individuals across 32 States and Union Territories.[30]

Emerging of Good Practices

A few months into the pandemic, several good practices adopted by states began to emerge (Figure 10). Effective case management strategies= highlighted the need for tailored local responses to reduce COVID-related fatalities. Identifying and monitoring high-risk populations, such as the elderly and those with co-morbidities, allowed for prompt medical intervention at the first sign of deteriorating symptoms.

Figure 10: Models of COVID-19 mitigation and management that emerged from states

Source: *Original*

States like Gujarat collaborated with pulmonologists and critical care experts to improve the management of severely ill COVID patients, while a team in Ahmedabad initiated tele-mentoring to support ICUs treating these patients. Kerala prepared comprehensive route maps for contact tracing, while Tamil Nadu developed a six-layered protection model based on Artificial Intelligence and robotics for detecting COVID-19 symptoms. Jharkhand deployed 'Co-Bots' to deliver food, water, and medicines to patients.

Aspirational Districts also demonstrated innovation. Wayanad trained doctors, nurses, and frontline workers in COVID-19 management using virtual platforms, while Washim established fever clinics for early detection of COVID-19. Cities like Panchgani in Maharashtra adopted decentralized segregation for managing COVID-19 waste, while Nandyal Municipal Corporation in Andhra Pradesh arranged mobile handwashing facilities in slum areas. These efforts showcased localized and creative responses to the challenges posed by the pandemic.

'4P' Model of COVID-19 Management

India's Prime Minister emphasized that effective governance should follow the '4P' principle -- People, Public, and Private Partnership. India enacted this principle by engaging all levels of government, the private sector, civil society, and citizens to tackle the COVID-19 crisis. In response to the Prime Minister's call, state governments worked closely with the central government to control the virus's spread. Collaborations with the private sector and civil society significantly bolstered government efforts, resulting in the rapid development of the *Aarogya Setu* app and the COVID vaccine, the establishment of a new industry for personal protective equipment as well as several innovations from start-ups, including robots for sanitization and delivery of essentials.

Civil society organizations partnered with governments to create COVID-19 control rooms, facilitate food delivery, and engage self-help groups in mask and sanitizer production while supporting livelihoods during the lockdown. A key achievement was engaging 1.3 billion people as partners with the government in fighting COVID-19.[31] The Prime Minister's advocacy for mask-wearing, social distancing, and hand hygiene led to widespread behavioural changes, helping the nation adopt a 'new normal.' This public mobilization likely contributed to the relatively low impact of COVID-19 across some of India's poorest regions.

LESSONS LEARNED

Health Outcomes and Economic Impact of Lockdowns

The COVID-19 pandemic emphasized the delicate balance between health outcomes and economic sustainability during

prolonged lockdowns. Efforts to develop nuanced models accounting for age-related mortality rates and assessing 'smart' lockdowns highlighted the potential for mitigating economic disruptions. Tailored approaches are essential for India, given its diverse demographic and economic conditions. For example, combining mobility restrictions with decentralized, community-based support systems could ensure essential services while minimizing economic harm.

Importance of Decentralization and Community Engagement

Decentralized strategies proved vital in addressing pandemic challenges, particularly in resource-limited settings. Community engagement was central to these efforts, with local change agents and grassroots organizations playing a key role in tailoring responses to specific needs. For instance, mobile handwashing facilities were implemented in urban slums where conventional hygiene infrastructure was lacking, showcasing how innovation and localized action can enhance public health measures.[32] Strengthening municipal governance through collaboration with slum leaders and urban local bodies could further improve pandemic resilience.

Public Awareness and Communication

Public awareness campaigns during COVID-19, including the use of apps like *Aarogya Setu*, demonstrated the power of technology in disseminating health information. These platforms promoted preventive measures such as mask usage and social distancing. However, combating misinformation, particularly on social media, remains a critical gap. Tailored communication strategies that consider linguistic and cultural diversity are essential. For instance, messages translated into regional languages and delivered via community radio or visual media can ensure broader reach. Partnering with civil society organizations experienced in addressing stigma related to TB and HIV could enhance the impact of these initiatives.

Long COVID and Implications for Healthcare Systems

Long COVID poses significant challenges for healthcare systems and policy planning, as it involves persistent symptoms like fatigue, cognitive dysfunction, and cardiovascular issues. Research in India has shown that nearly a quarter of COVID-19 survivors experience ongoing symptoms even a year post-recovery. This has implications for resource allocation, requiring specialized clinics, multidisciplinary teams, and telemedicine services to address the complex needs of these patients.

Mental health initiatives, such as the establishment of counselling hotlines and community support groups, have helped mitigate psychological distress. However, areas for improvement remain, particularly in expanding access to mental health care in rural areas and integrating mental health into primary healthcare frameworks. Lessons can be drawn from successful programs like Kerala's *DISHA* helpline, which provided round-the-clock mental health support during the pandemic.

Leveraging Digital Health and Technology

The pandemic catalysed advancements in digital health, creating opportunities to address healthcare challenges more efficiently. Telemedicine adoption surged, enabling remote consultations and monitoring for individuals with chronic illnesses. Wearable devices are now being designed to monitor conditions such as diabetes and cardiovascular health in real time, offering proactive care options.

Future innovations, including AI-powered diagnostic tools and robotic surgical systems, could transform healthcare delivery, especially in underserved rural areas. For example, AI-assisted solutions like virtual health assistants could address the shortage of qualified doctors in remote regions. Furthermore, integrating blockchain for secure medical record storage and sharing can enhance patient care continuity across different health facilities.

BROADER HEALTH SYSTEM RECOMMENDATIONS

Strengthening Public Health Infrastructure

India must significantly augment its health budget, focusing on critical sectors such as nutrition, water, and sanitation. States, accounting for 66% of healthcare expenditures, should allocate at least 8% of their budgets to healthcare, as per the National Health Policy (NHP) 2017 and Fifteenth Finance Commission recommendations.[33] While India allocated 2.1% of GDP to healthcare in 2023, this remains far below the 10 to 11% spent by countries like Japan and Germany, whose public systems deliver far superior health outcomes.[34] Preventive healthcare must be prioritized to reduce the disease burden and avoid overwhelming facilities, as seen during the COVID-19 pandemic. A comprehensive approach integrating initiatives like *Swachh Bharat Mission* and *POSHAN Abhiyaan* should address both medical and social determinants of health. Establishing a central authority, such as an empowered National Centre for Disease Control (NCDC), can lead efforts in disease surveillance, public education, and health regulation. Interdisciplinary expert committees should also be constituted for emergency response at all levels.

Investing in Vaccine and Pharmaceutical Research

Strengthening vaccine and therapeutic research requires connecting multidisciplinary research units and creating disease-specific data repositories. Innovation and

collaboration are essential for progress in this area. Expanding facilities like VRDLs is critical to expedite development, as demonstrated by Hong Kong, Japan, and Singapore in responding to COVID-19.[35]

Enhancing Digital Health Solutions

Expanding telemedicine services can significantly improve healthcare accessibility, particularly in underserved regions. Fully operationalizing the Integrated Health Information Portal (IHIP) and strengthening the Integrated Disease Surveillance Programme (IDSP) with improved digital connectivity and private-sector engagement are vital steps. Additionally, leveraging tools such as artificial intelligence, electronic health records, and wearable diagnostics can modernize healthcare delivery and enhance pandemic preparedness.

Addressing Inequalities in Healthcare Access

Reducing disparities in healthcare access requires extending healthcare and social protections to at-risk groups, such as the elderly living alone and the urban homeless. Fully operationalizing *Ayushman Aarogya Mandirs* (AAMs) will enhance community outreach, enabling early disease detection and promoting hygiene, inspired by Nigeria's successful Ebola response. Community engagement is crucial, and civil society organizations, along with frontline health workers, should be empowered to close monitoring gaps and reach underserved populations, effectively.

Public Health Surveillance for Pandemic Preparedness

Strengthening the IDSP requires addressing critical challenges such as high vacancy rates, lack of standardized outbreak reporting, and limited geographic coverage. Expanding the list of notifiable diseases and mandating private-sector data sharing under health acts will enhance its efficiency. Developing regional or state institutions for reliable population-level data is essential along with the training frontline personnel in syndromic reporting using basic tools and diagnostics. Encouraging private-sector involvement in manufacturing medical supplies, including ventilators and infection control equipment, is necessary to bolster preparedness and innovation in this domain.

CONCLUSION

The COVID-19 pandemic underscored the importance of preparedness and systemic resilience in addressing health crises. While India's proactive measures, such as early lockdowns, aggressive testing, and rapid vaccine development, mitigated the immediate impact, the crisis exposed critical challenges like underfunded healthcare, supply chain vulnerabilities, and inequalities.

Strengthening public health infrastructure, increasing health spending, and prioritizing preventive care are essential. Scaling up investment in vaccine and pharmaceutical research, along with leveraging digital health technologies like telemedicine and AI, can improve access and readiness, particularly in underserved areas. Addressing healthcare inequalities and empowering community responses remain critical, supported by robust surveillance systems and public-private partnerships.

India's pharmaceutical strength and initiatives like *Aatmanirbhar Bharat* and Vaccine Maitri position it as a global leader in affordable healthcare solutions. By embedding these lessons into long-term policies under the 'One World One Health' framework, India can build a resilient healthcare system, safeguard public health, and enhance global health security.

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