

Global reduction in morbidity and mortality due to vaccine development against major infectious pathogens, 1974-2024 (Review)

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Abstract. Vaccination remains one of the most effective and equitable interventions in public health, preventing infectious disease and transforming global survival. Since the launch of the World Health Organization Expanded Programme on Immunization in 1974, vaccine innovation and coordinated international partnerships have reshaped child health worldwide. The present review synthesizes evidence from the Global Burden of Disease Study, WHO/UNICEF, Gavi and Our World in Data to evaluate global, regional and pathogen-specific reductions in disease burden due to vaccination from 1974 to 2024. Data on coverage rates, deaths averted and inequities in access were analyzed to assess progress and remaining challenges. Since 1974, vaccination programs have saved the lives of ~150 million children globally, reflecting one of the greatest humanitarian achievements in history. Global coverage for major childhood vaccines, including DTP3, polio, measles and hepatitis B, has increased from <20% in 1980 to >80% in 2024. Africa and South-East Asia accounted for almost 70% of the total lives saved, highlighting the success of targeted campaigns in high-burden regions. Measles-related deaths declined from 2.6 million (1974) to 73,000 (2024), and pneumococcal vaccination alone prevented approximately 400,000 deaths in 2019. However, inequities persist: In 2022, 89 countries reported vaccine stock-outs, predominantly in low- and middle-income regions. Between 1974 and 2024, global vaccination efforts have averted hundreds of millions of deaths, eliminated smallpox, and nearly eradicated poliomyelitis. Sustaining these gains and reaching the remaining unvaccinated populations will require equitable distribution, stronger health systems, and continued investment to fulfil the Immunization Agenda 2030 goals.

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Contents

1. Introduction
2. Data and literature search
3. Global reduction in morbidity and mortality rates due to vaccination (1974-2024)
4. Global expansion of vaccine coverage and mortality reduction
5. Lives saved by vaccination across continents
6. Regional and pathogen-specific impact of vaccination (1974-2024)
7. Poliomyelitis (polio)
8. Measles
9. Smallpox eradication and global impact of vaccination
10. Reduction in geographic endemicity and public health legacy
11. Impact of hepatitis B, rotavirus and rubella vaccination (1980-2024)
12. Pneumococcal disease and vaccine impact
13. Impact of bacterial vaccination on global child health (1980-2024)
14. Global inequities and vaccine stock-outs (2022-2024)
15. Overview
16. Conclusion and future perspectives

1. Introduction

Vaccination is among the most effective public health interventions in human history. Since the development of vaccines, the burden of numerous infectious diseases has declined greatly, leading to major improvements in child and adult survival and global life expectancy. Between 1974 and 2024, vaccination programs contributed to the control or elimination of several vaccine-preventable diseases (VPDs), including smallpox, polio, diphtheria, pertussis and measles, and more recently helped reduce the impact of the COVID-19 pandemic (1-3).

The development of vaccines has progressed significantly since the early work of Edward Jenner (3). Advances in vaccine science and technology, including genomics and effectiveness of vaccines, have improved the safety and effectiveness of vaccines. These developments have strengthened global vaccination programs and continue to be critical in the prevention of infectious diseases worldwide (4,5).

The concept of vaccination was introduced in 1796 by Edward Jenner (3), who produced the smallpox vaccine. This milestone discovery clarified the immunization of the body against disease by immune system induction through introducing or injecting a less virulent virus or pathogen. Another breakthrough in vaccination discovery and development was made by Louis Pasteur. He introduced the vaccine against anthrax and rabies in the 19th century. The major development of vaccines occurred in the 20th century as numerous vaccines were created against a number of viral diseases: Measles, pertussis, tetanus, diphtheria, rubella and mumps (6,7).

The traditional method of vaccine development depends on generating an inactivated or a live, yet attenuated pathogen. Live attenuated vaccines provide more effect and more potent immunity and last longer; however, they carry risks when used in immunocompromised individuals. An inactivated vaccine is a second traditional type of vaccine that uses a dead pathogen to induce the immune system. This type of vaccine is safer, but requires several doses to boost immunity. These two classical methods of vaccination became the principles of individual, herd and global immunization (8).

Recently, advances have occurred in the development of vaccines and vaccine technology. In addition to traditional vaccines, new vaccines are currently being developed using different scientific and medical technologies. One of the newer vaccine platforms is the subunit vaccine, which contains only specific parts of the pathogen, such as purified proteins, and uses them to stimulate an immune response (e.g., hepatitis B vaccine) (6,7). Another key development is the conjugate vaccine. In this platform, the antigen of the pathogen is linked to a carrier protein to improve the immune response, as observed in the *Haemophilus influenzae* type b vaccine (9). More recently, genetic vaccine platforms, such as DNA and RNA vaccines, as well as viral vector vaccines, have been developed (10,11). DNA and RNA vaccines function by introducing genetic material from the pathogen into host cells, allowing the body to produce pathogen proteins and trigger an immune response. This approach was successfully used in vaccines developed against COVID-19. Viral vector vaccines use a harmless virus to deliver pathogen genes into host cells, where the pathogen proteins are produced, and immunity is induced. These vaccines were also widely used during the COVID-19 pandemic (10).

Challenges remain in fighting pathogens through vaccination, despite all the mentioned successes. In areas of poor vaccination practice, conflict and poor healthcare, morbidity and mortality rates remain high due to highly infectious diseases. In 2021, >25 million children could not obtain routine vaccinations due to disruptions caused by global COVID-19 and increasing vaccine hesitancy during the pandemic (12). Equality in access to vaccine sources is restricted by a number of factors, including financial and political, particularly in low-income countries (13). The last and unmentioned issue in vaccination is a lack of public trust in science. This hampers the vaccination program and campaign even in high-income countries (14).

The present review aimed to provide a comprehensive analysis of the decline in global morbidity and mortality in humans, associated with vaccine development from 1974 to 2024. This data synthesis depends on information available in the Global Burden of Disease (GBD), World Health

Organization (WHO) vaccination records, Gavi, Our World in Data, and epidemiological literature publications. The impact of public health vaccination was calculated over the past 50 years. The present review also discusses how different regions have benefited from vaccines, identifies gaps in coverage, and emphasizes the need for sustainable immunization strategies to address current and emerging global health threats.

2. Data and literature search

The present review employs a descriptive, data-integrative approach to evaluate the global, regional, and pathogen-specific impact of vaccination on morbidity and mortality from 1974 to 2024. Data were obtained exclusively from open-access, validated international databases, including the WHO, United Nations Children's Fund (UNICEF), WHO/UNICEF estimates of national immunization coverage (15), the GBD Study (16), Gavi, the Vaccine Alliance progress reports, and Our World in Data (OWID) vaccination datasets. Supplementary peer-reviewed literature was identified through PubMed and Scopus using combinations of the search terms 'vaccination', 'immunization coverage', 'vaccine-preventable diseases' and 'child mortality'. Only peer-reviewed articles published in the English language were included, focusing on studies reporting vaccination coverage, VPDs and mortality trends.

Data extraction followed a standardized protocol. Vaccination coverage rates, reported cases, mortality estimates and modelled 'deaths averted' were extracted from publicly available datasets including WHO/UNICEF WUENIC (<https://www.who.int/data/immunization>), the GBD (IHME) database (<https://www.healthdata.org/gbd>), Gavi progress reports (<https://www.gavi.org>), and OWID vaccination datasets (<https://ourworldindata.org/vaccination>). All datasets were accessed between June and October, 2025. Extracted variables included vaccine coverage (%), reported cases, mortality rates, and estimated deaths averted by pathogen and region. Data cleaning and harmonization were performed by aligning datasets to WHO regional classifications and standardizing time-series values. Analyses and visualizations were conducted using Microsoft Excel and Python (using the Matplotlib library).

Estimates of 'deaths averted' were derived from previously published modelling frameworks used by the GBD (IHME), WHO and Gavi analyses. These models estimate the difference between observed mortality under current vaccination coverage and a counterfactual scenario without vaccination, integrating demographic data, pathogen-specific case-fatality rates, vaccine efficacy and historical coverage trends. The present review did not generate new models, but synthesized these validated estimates from publicly available datasets.

All quantitative indicators, coverage rates, cases, death rates and deaths averted were extracted for the period 1974-2024 and harmonized to WHO regional classifications (Africa, the Americas, South-East Asia, Europe, Eastern Mediterranean and Western Pacific). Data from different sources were cross-checked to reduce inconsistencies. When discrepancies occurred between databases, estimates from the WHO or the GBD study were prioritized due to their standardized methodology. Missing values were addressed using the closest available year estimates or modelled values

reported by the respective databases. Data were cleaned and normalized to ensure comparability across time and regions. Deaths averted were derived from online database-modelled estimates integrating mortality surveillance, demographic data, and counterfactual no-vaccination scenarios.

Figures and charts were created using Microsoft Excel and Python (Matplotlib library) to visualize long-term trends, regional disparities and vaccine-specific impacts. Where possible, results were expressed in absolute numbers (millions of lives saved) and relative change (%) from baseline years to illustrate progress over time. No human or animal subjects were involved; all analyses were based on publicly available secondary data.

3. Global reduction in morbidity and mortality rates due to vaccination (1974-2024)

The worldwide decline in morbidity and mortality rates resulting from vaccination represents one of the greatest triumphs in modern public health. This achievement has been enabled through sustained advances in immunological science, innovation in vaccine formulation and coordinated global partnerships. Landmark initiatives such as the WHO's Expanded Programme on Immunization (EPI), launched in 1974, along with global alliances including Gavi, the Vaccine Alliance, and UNICEF, transformed access to life-saving vaccines in low- and middle-income countries (17-19). The introduction of six essential vaccines, against poliomyelitis, measles, pertussis, diphtheria, tuberculosis and tetanus, under the EPI framework laid the foundation for today's global immunization infrastructure (20).

Since the establishment of the EPI, vaccination programs have saved the lives of ~150 million children, according to the WHO (2024) (21). This extraordinary achievement demonstrates the transformative impact of immunization on human survival, which prevented infectious diseases that once claimed millions of lives annually and reshaped global child health, life expectancy and socioeconomic stability (22).

4. Global expansion of vaccine coverage and mortality reduction

Since the initiation of the EPI, global vaccination coverage has markedly increased, accompanied by a substantial decline in infant mortality rates (Fig. 1). Between 1980 and 2024, coverage with three doses of the diphtheria, tetanus and pertussis (DTP), polio and hepatitis B vaccines increased from <20% to >80-85%, while rubella coverage reached ~73% and *Haemophilus influenzae* type b (Hib) vaccination increased to 78%. Newly introduced vaccines, such as rotavirus (2006) and pneumococcal conjugate vaccine (2008) reached global coverage levels of 59 and 67%, respectively (15).

Parallel to this increase in immunization, the global infant mortality rates decreased from ~10.2 deaths per 1,000 live births in the absence of vaccination to 2.8 deaths per 1,000 with full vaccine coverage, corresponding to an estimated 73% reduction in infant deaths. Without vaccines, the modelled trajectory indicates mortality would have remained nearly twice as high throughout the period. This dual trend underscores how increasing vaccine access directly translates into

reduced childhood mortality, reflecting decades of global coordination under the Immunization Agenda 2030 (23,24).

5. Lives saved by vaccination across continents

The cumulative impact of vaccination on mortality reduction is immense. Between 1974 and 2024, vaccines collectively averted hundreds of millions of deaths, with the largest benefits observed in Africa and South-East Asia, regions historically burdened by infectious diseases and limited healthcare infrastructure (Fig. 2). In Africa, the number of lives saved increased from <1 million in 1980 to >53 million by 2024, while in South-East Asia, this value increased from <1 million to 38 million.

The Eastern Mediterranean Region reported >25 million lives saved, and although the Americas and Europe achieved smaller absolute gains (16 million and 7 million, respectively), early eradication programs eliminated poliomyelitis and diphtheria decades earlier (25,26). Collectively, these data highlight that consistent immunization efforts have prevented tens of millions of deaths and alleviated global health inequities (17,18,23).

6. Regional and pathogen-specific impact of vaccination (1974-2024)

The global and regional health benefits of vaccination are illustrated in Figs. 3 and 4, which together highlight the overall and pathogen-specific lives saved across continents between 1974 and 2024. Fig. 3 summarizes the regional distribution of total lives saved, while Fig. 4 further classifies these outcomes by specific pathogens responsible for the mortality reductions.

The graph depicted in Fig. 3 presents cumulative lives saved by childhood vaccination programs across major world regions. The data show that Africa and South-East Asia accounted for the greatest absolute gains, together representing over two-thirds of the global total (23). These regions experienced rapid mortality declines following the expansion of immunization programs under the EPI and subsequent Global Vaccine Action Plan initiatives (17,18). As illustrated in Fig. 3, the steep increase in lives saved in these regions reflects the large population size and historically higher burden of VPDs prior to widespread immunization. Conversely, Europe, the Americas and the Western Pacific reported smaller numerical increases, reflecting earlier achievement of high coverage and earlier control of VPDs such as measles, diphtheria and poliomyelitis (25,26).

Building on these regional trends, Fig. 4 provides a pathogen-level breakdown of lives saved across global regions. Unlike Fig. 3, which presents the overall regional totals, Fig. 4 illustrates how different vaccines contributed to mortality reduction within each region. Measles and tetanus dominate in Africa and South-East Asia, contributing the most prevented deaths due to their historically high case-fatality rates and rapid post-vaccine declines. Regions with long-standing immunization infrastructure, such as Europe, the Americas and the Western Pacific, exhibit more balanced distributions, with notable impacts from hepatitis B, pertussis, and pneumococcal vaccines. The Eastern Mediterranean displays mixed patterns, with reductions in neonatal tetanus and measles mortality

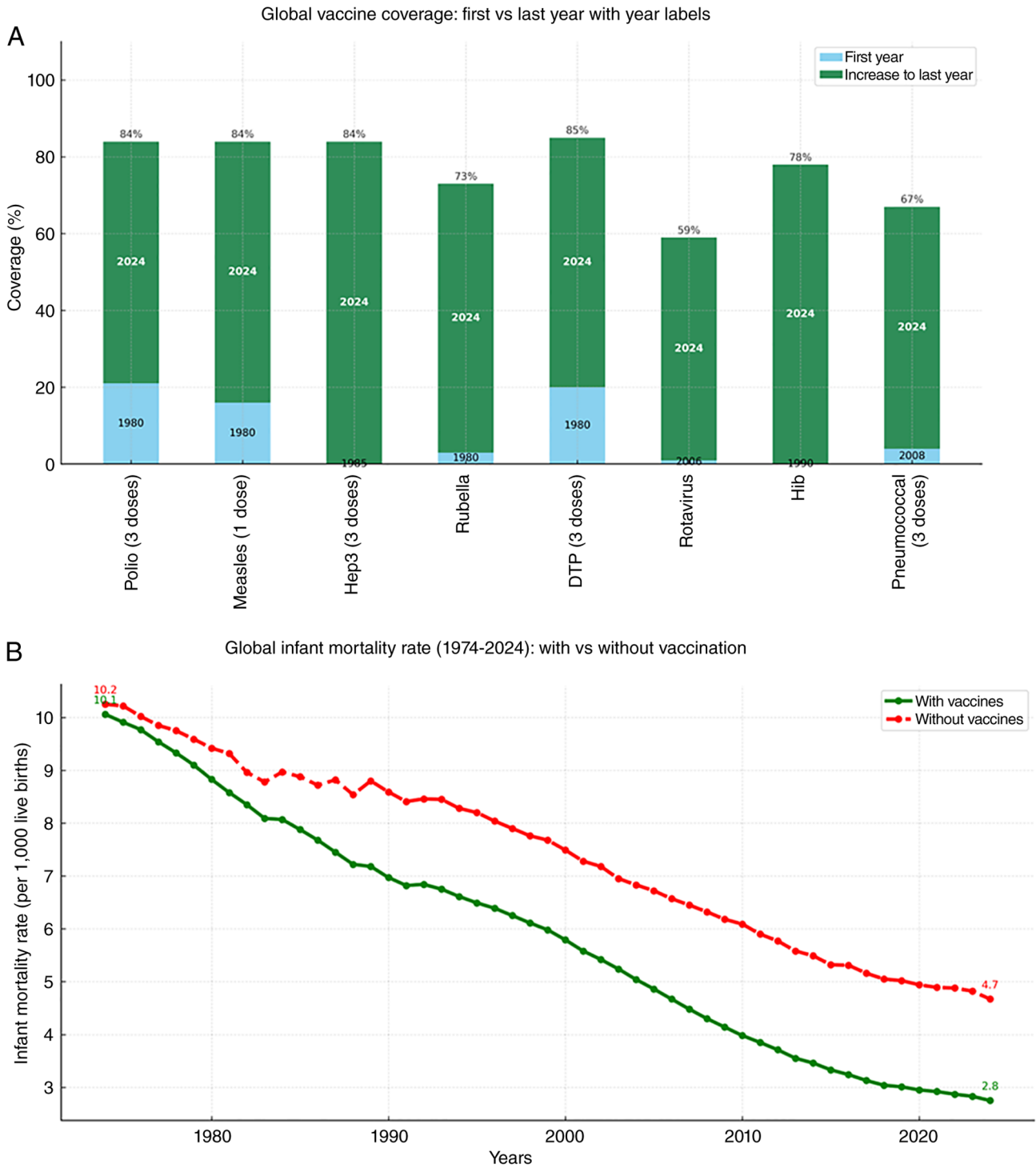


Figure 1. Global vaccination coverage and infant mortality, 1974-2024. (A) Expansion of coverage for major childhood vaccines between the first and most recent years reported. (B) Global infant mortality rate with and without vaccination, exhibiting a 70-75% decline attributable to immunization programs. Source: WHO, UNICEF, IHME and Our World in Data (2024).

driving steady improvements in child survival. These patterns emphasize how the same vaccines produce region-specific impacts depending on baseline incidence, health-system capacity, and timing of vaccine introduction (17,18,23,25).

7. Poliomyelitis (polio)

Poliomyelitis is a highly contagious viral disease that predominantly affects young children, leading to irreversible

paralysis in a small proportion of infections (27). The global control of polio represents one of the most significant achievements of modern immunization efforts. Since the launch of the Global Polio Eradication Initiative in 1988, wild poliovirus transmission has been eliminated from five of six WHO regions, representing over a 99% reduction in global incidence, from an estimated 350,000 cases annually to <200 cases in 2021 (18,28,29). While wild poliovirus type 1 persists in Afghanistan and Pakistan, multiple nations continue to

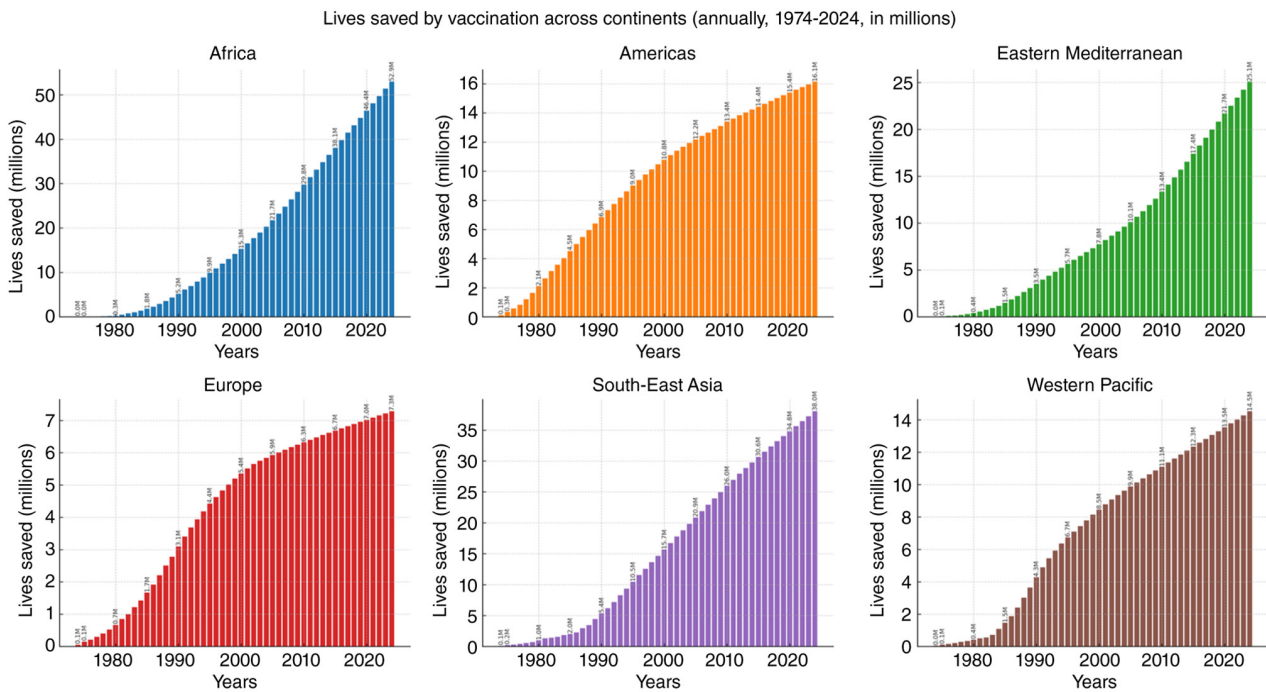


Figure 2. Lives saved by vaccination across continents, 1974-2024 (in millions). The greatest gains occurred in Africa and South-East Asia, reflecting intensified global immunization efforts and improvements in vaccine access. Source: WHO, Gavi, IHME and Our World in Data (2024).

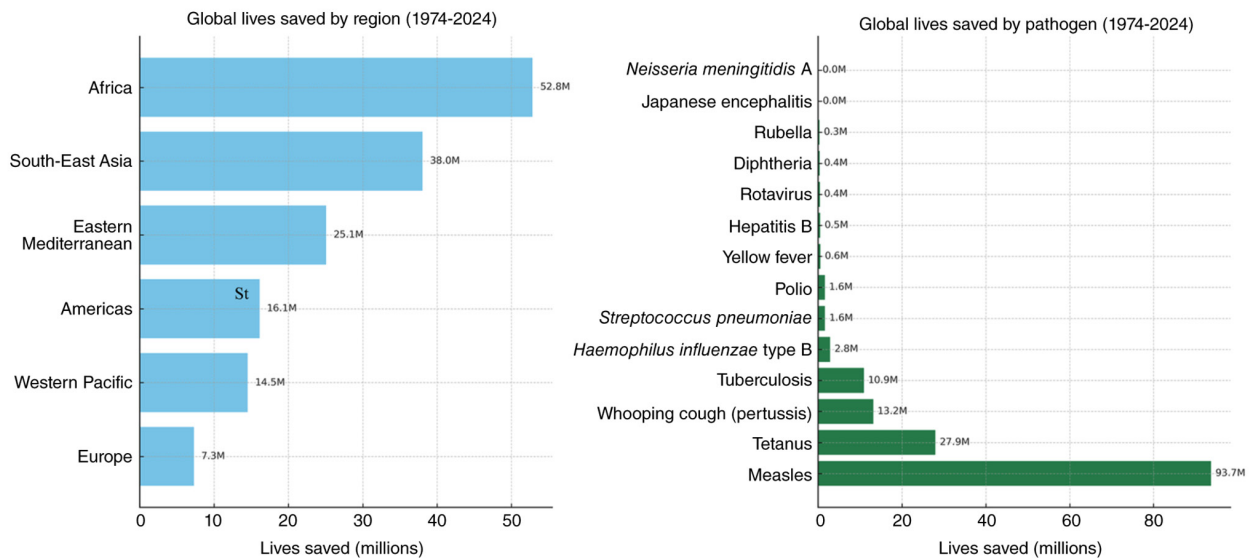


Figure 3. Global lives saved by vaccination, 1974-2024. The left panel illustrates cumulative lives saved by childhood vaccinations across major world regions from 1974 to 2024, with Africa and South-East Asia contributing the largest gains. The right panel illustrates the lives saved by pathogen. Source: WHO, Gavi, IHME, and Our World in Data (2024).

face outbreaks of circulating vaccine-derived polioviruses (cVDPVs). In 2023 alone, eight new countries reported cVDPV outbreaks, underscoring the critical need for vigilant surveillance and the maintenance of high immunization coverage (5,19). This progress stems from massive expansion in oral and inactivated polio vaccine coverage, improved surveillance and targeted supplementary immunization campaigns in endemic zones.

Globally, three-dose polio (OPV3/IPV3) vaccination coverage increased from 21% in 1980 to 84% in 2024 (Fig. 5). Rapid gains were observed during the 1980s and

early 1990s, when coverage increased from 21 to 70%, in parallel to the establishment of the EPI in low- and middle-income countries. Between 1990 and 2010, global coverage stabilized at ~70-75%, followed by renewed progress to 86% by 2015, before levelling near 84% in 2024. Regional variations persist; coverage exceeds 90% in the Americas, Europe, and Western Pacific but remains around 75-80% in parts of Africa and the Eastern Mediterranean (21,24,15,30).

Integration with previous analyses (Figs. 2-4) highlights the relatively smaller contribution of polio to total lives saved

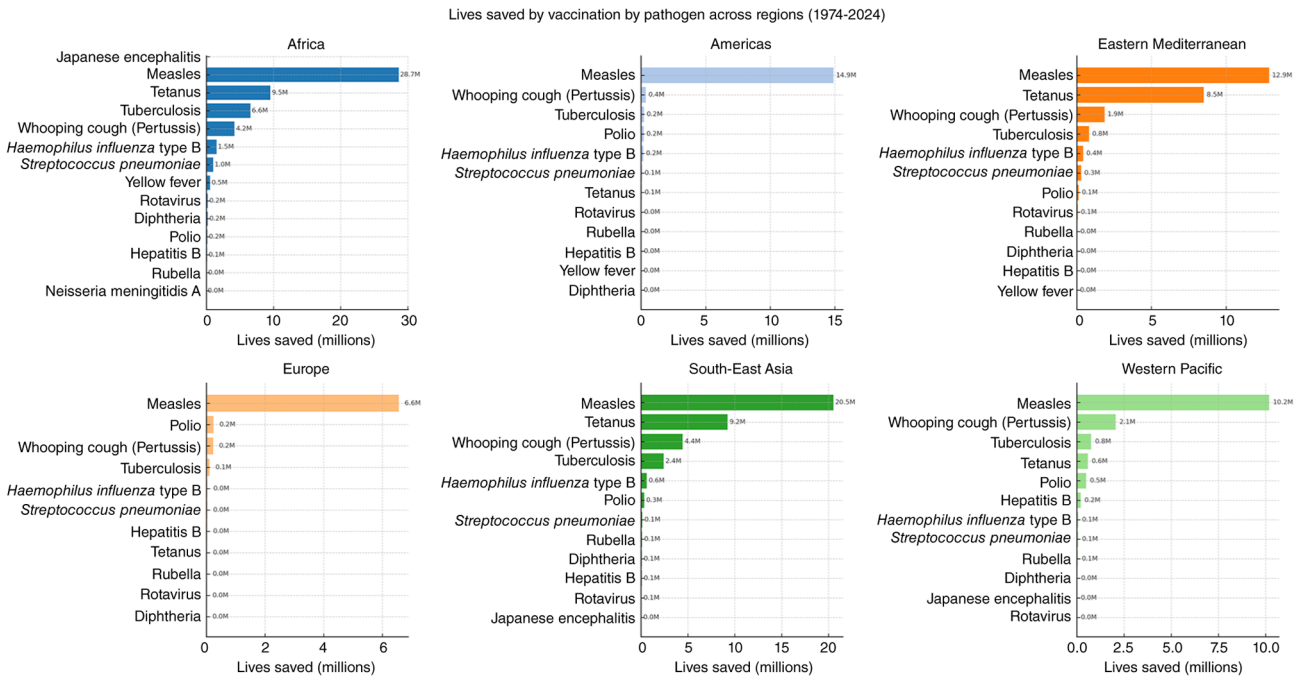


Figure 4. Lives saved by pathogen across global regions, 1974-2024. Each panel represents the cumulative lives in one region saved by vaccination against major pathogens from 1974 to 2024. Bar lengths correspond to lives saved (in millions), highlighting regional differences in pathogen-specific impact. Measles and tetanus dominate in Africa and South-East Asia, while the Americas, Europe and the Western Pacific exhibit more balanced distributions. Source: WHO, IHME, UNICEF and Our World in Data (2024).

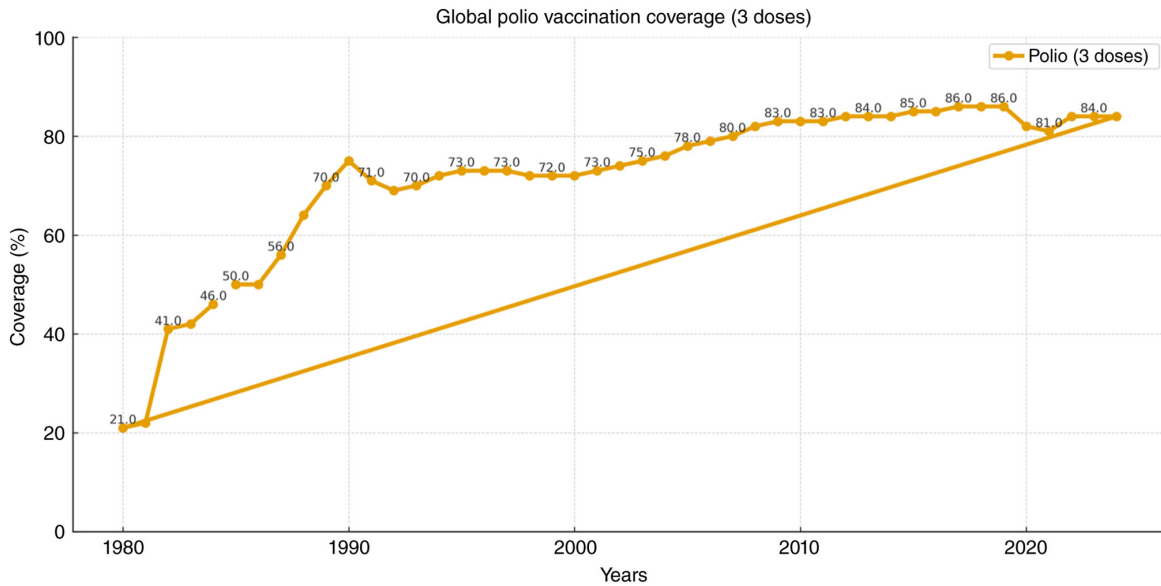


Figure 5. Global coverage of the polio vaccine (three doses), 1980-2024. Global trend in polio (OPV3) vaccination coverage among 1-year-old children based on WHO/UNICEF estimates (2024 revision). Data points represent annual coverage rates with values shown for alternate years to enhance readability. The figure illustrates the substantial global increase in OPV3 coverage since the 1980s, reflecting the expansion of routine immunization programs and international polio eradication initiatives. Source: WHO/UNICEF WUENIC Dataset 2024; Our World in Data; GPEI (2021).

compared with measles or tetanus, largely due to the fact that global eradication efforts rapidly reduced incidence rates to near zero. Nevertheless, millions of children avoided lifelong disability and mortality, and sustained immunization remains critical to prevent re-emergence. The final pockets of wild poliovirus transmission, currently limited to Afghanistan and Pakistan, pose ongoing challenges due to conflict, vaccine hesitancy and surveillance gaps (5).

8. Measles

Measles historically caused millions of deaths in children; however, mortality has sharply declined following global vaccination scale-up. According to the WHO, worldwide measles mortality rates decreased from ~2.6 million deaths in 1950 to ~73,000 in 2021 (31). Between 2000 and 2023, vaccination is estimated to have prevented 60 million deaths (17,32,33).

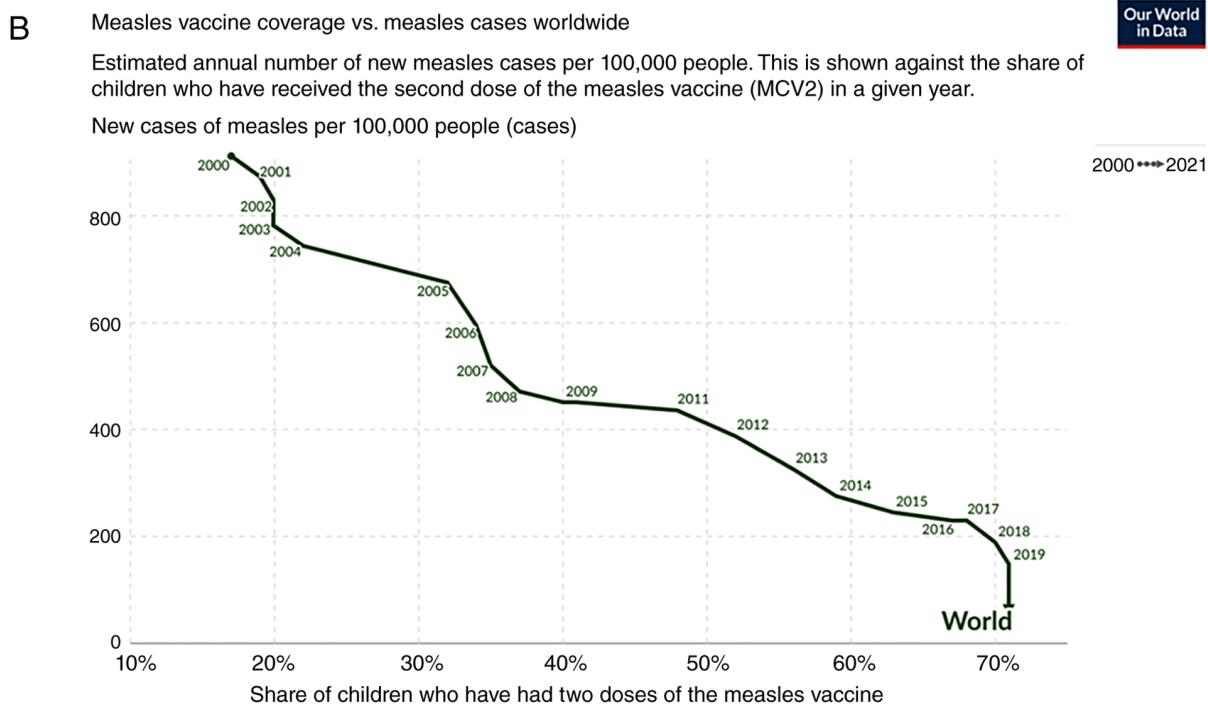
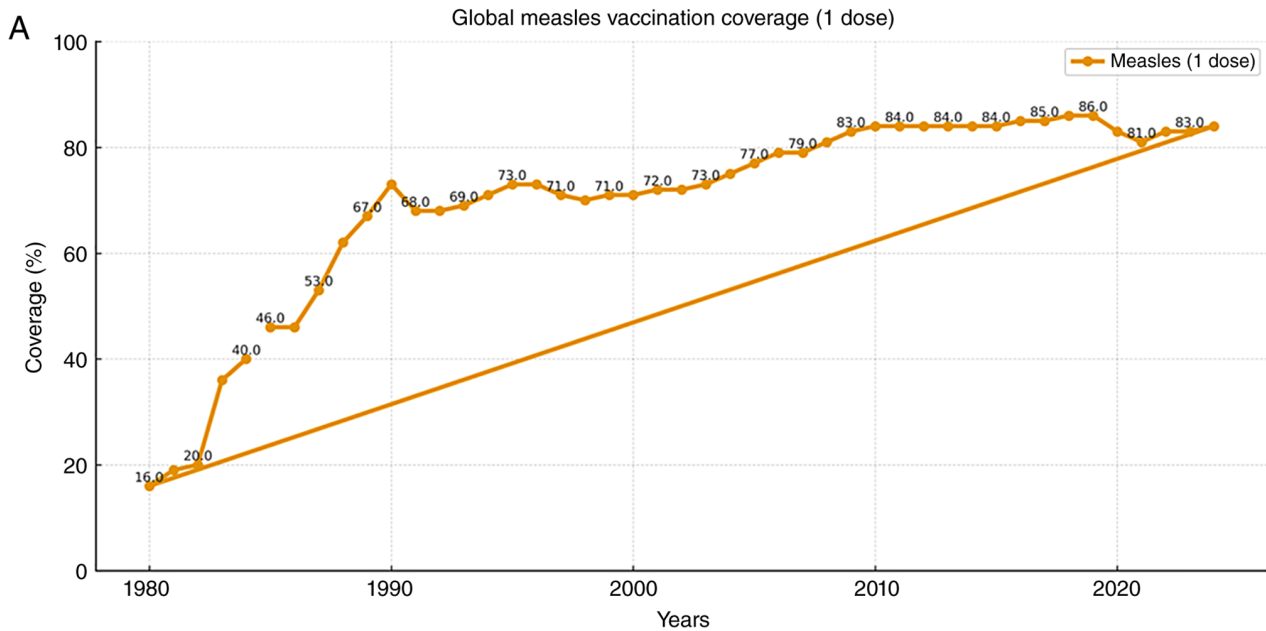


Figure 6. Global measles vaccination and disease burden, 1980-2024. (A) Global measles (MCV1) coverage increased from 16% in 1980 to ~84% in 2024, after peaking at ~86% in 2018-2019, decreasing to ~81% in 2020-2021, and rebounding thereafter (WHO/UNICEF WUENIC 2024). (B) As MCV2 coverage increased from ~15-20% (early 2000s) to ~70% (2019-2021), estimated measles cases decreased from ~900 per 100,000 (2000) to ~100 per 100,000 (2019), illustrating the inverse association between coverage and incidence (IHME/WHO/UNICEF via Our World in Data).

Consistent with these gains, global MCV1 coverage increased from 16% (1980) to ~84% (2024), with a plateau of 84-86% in 2012-2019, a pandemic-related dip to ~81% (2020-2021), and recovery to 83-84% (2023-2024) (15) (Fig. 6A). Over the same period, the rise in MCV2 coverage from roughly ~15-20% in the early 2000s to ~70% by 2019-2021 was associated with a ~90% reduction in estimated measles cases, from ~900 per 100,000 (2000) to ~100 per 100,000 (2019; IHME/WHO/UNICEF; Fig 6B). Regionally, the largest mortality declines occurred in Africa and South-East Asia, which together accounted for most of the global burden reduction (16) (Fig. 7). These

trends reaffirm that sustained two-dose coverage and catch-up campaigns are pivotal to achieving and maintaining measles mortality elimination (21,30,34,35).

9. Smallpox eradication and global impact of vaccination

Smallpox remains the only infectious disease ever eradicated by human intervention, marking one of the greatest achievements in global public health. Prior to eradication, smallpox was responsible for 300-500 million deaths during the 20th century alone and was one of humanity's most

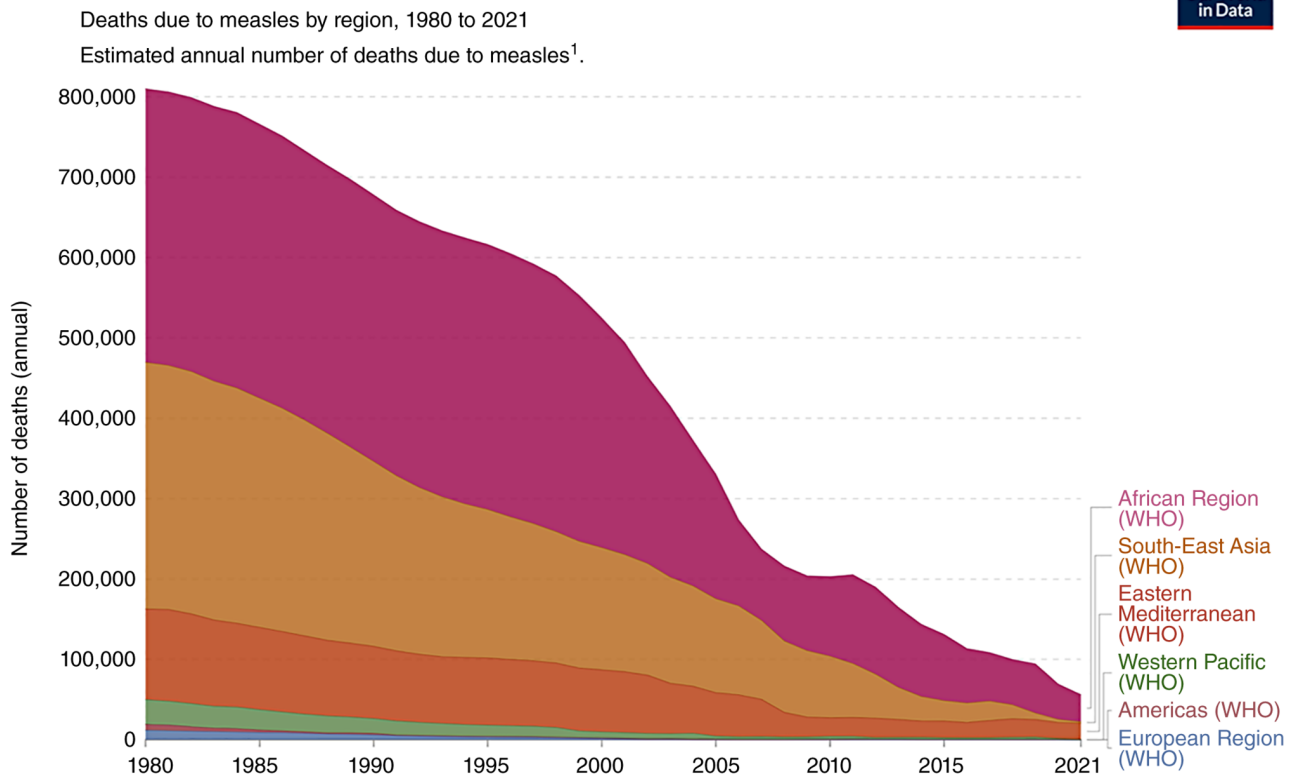


Figure 7. Deaths due to measles by region, 1980-2021. Annual global measles deaths decreased from ~800,000 in 1980 to ~73,000 in 2021, with the steepest reductions in Africa and South-East Asia; deaths in the Americas and Europe decreased to near zero by the 2000s (IHME GBD 2024; OWID).

lethal viral diseases for millennia (36,37). The introduction of vaccination, first pioneered by Edward Jenner in 1796, eventually culminated in a coordinated global effort led by the WHO.

Global decline in smallpox cases. The global number of reported smallpox cases markedly decreased from >400,000 in 1920 to complete eradication by 1980 (Fig. 8). Data compiled from WHO and IHME archives indicate repeated epidemics during the early 20th century, with major spikes in 1947-1951, when reported cases exceeded 600,000 per year. The establishment of the WHO Global Smallpox Eradication Program in 1959, followed by the intensified eradication campaign in 1967, resulted in an exponential decline to fewer than 1,000 cases worldwide by 1977. The final naturally occurring case was documented in Somalia in 1977, and in May 1980, the WHO officially certified the global eradication of smallpox (21,36,38).

10. Reduction in geographic endemicity and public health legacy

The number of countries where smallpox remained endemic decreased from >50 nations in 1920 to none by 1980 (35). Africa and Asia initially accounted for the majority of the endemic regions, with ~45 African and 30 Asian countries; but by the late 1970s, both continents had achieved elimination. The Americas, Europe and Oceania eliminated the disease decades earlier, aided by earlier vaccine access and higher routine immunization rates (36,21). This reduction mirrored

the stepwise expansion of the WHO eradication program milestones (Table I).

Public health legacy. The eradication of smallpox prevented an estimated 60-100 million potential deaths per decade globally and saved >1 billion US dollars annually in vaccination and treatment costs (17,36,37). The success of the program became the blueprint for subsequent eradication initiatives, including those for polio and measles, and marked the start of modern global immunization governance, influencing the later EPI (1974) (36,37).

Smallpox eradication thus demonstrates the transformative potential of coordinated vaccination programs integrating scientific advancement, international collaboration and community-level surveillance. Its historical trajectory, from >400,000 cases per year in 1920 to zero after 1980, remains the benchmark for evaluating all future global disease-control strategies (21,39,40).

11. Impact of hepatitis B, rotavirus and rubella vaccination (1980-2024)

Between 1980 and 2024, the introduction and widespread adoption of vaccines against hepatitis B, rotavirus and rubella have significantly reduced global mortality and morbidity, particularly among children in low- and middle-income countries. As illustrated in Fig. 9, *hepatitis B* vaccination coverage increased from almost 0% in 1985 to 84% in 2024, following its inclusion in national immunization programs across all WHO regions. The rotavirus vaccine, introduced in 2006, exhibited

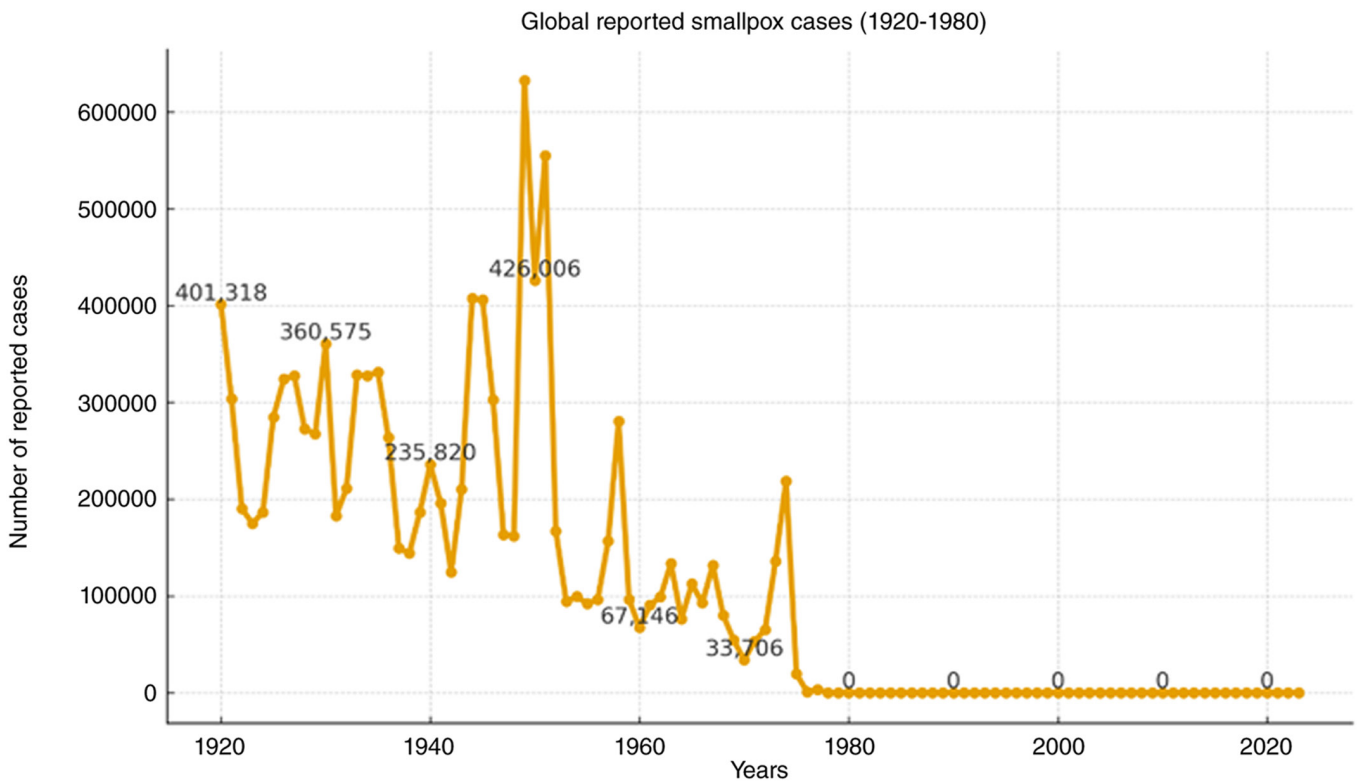


Figure 8. Global Smallpox Decline and Eradication (1920-1980). Reported global smallpox cases decreased from ~401,000 (1920) to zero (1980), exhibiting a >99.9 % reduction following WHO-led campaigns. Visualization by Saloni Dattani (Our World in Data, 2024). Underlying data: Fenner *et al* (1988); WHO (1980); WHO (2023).

Table I. Timeline of key milestones in the global smallpox eradication program (1959-1980).

Time	Action
1959	WHO launched the Global Smallpox Eradication Program
1967	Initiation of the Intensified Eradication Campaign, focusing on surveillance and containment rather than mass vaccination
1977	Initiation of the Intensified Eradication Campaign, focusing on surveillance and containment rather than mass vaccination
1980	WHO declared global eradication.

lives saved through vaccination since 1974, corresponding to ~53 million and 38 million lives, respectively. While measles and tetanus remain the leading contributors globally, hepatitis B vaccination has averted an estimated 0.5 million deaths, largely through the prevention of chronic liver disease and hepatocellular carcinoma, especially in Asia. Rotavirus vaccination has saved ~0.4 million lives, primarily among infants aged <5 years in Africa and South-East Asia, while rubella vaccination has prevented roughly 0.3 million deaths and thousands of congenital malformations, with transmission almost eliminated in the Americas and Europe by 2020. These achievements highlight how sustained investment in immunization, driven by the WHO, Gavi and IHME-led GBD programs, has reshaped global health by averting >1.2 million deaths from these three viral infections alone (21,30,35).

a rapid uptake, increasing from 1% to almost 59% coverage by 2024. Similarly, rubella vaccination increased from 3% in 1980 to 71% by 2024, reflecting coordinated global efforts to eliminate congenital rubella syndrome through combined measles-rubella campaigns (21). These vaccines have collectively transformed the global infectious disease landscape by preventing millions of deaths and disabling infections each year, particularly in regions where diarrheal diseases, neonatal infections, and viral hepatitis once accounted for a major share of childhood mortality (17,41,42).

The overall impact of these vaccines is further emphasized in Fig. 3, which demonstrates that Africa and South-East Asia together account for >70% of the total

12. Pneumococcal disease and vaccine impact

The pneumococcal conjugate vaccine (PCV3) represents one of the most impactful introductions in modern immunization history, particularly in reducing childhood mortality from pneumonia, meningitis and sepsis caused by *Streptococcus pneumoniae*. The global coverage of PCV3 has steadily increased since its introduction in the late 2000s, increasing from only 4% in 2008 to 67% in 2024 according to WHO/UNICEF (2024) estimates (21) (Fig. 10). This expansion followed the widespread adoption of PCV programs supported by Gavi, the Vaccine Alliance, and major donor partnerships, enabling rapid inclusion in low- and middle-income countries

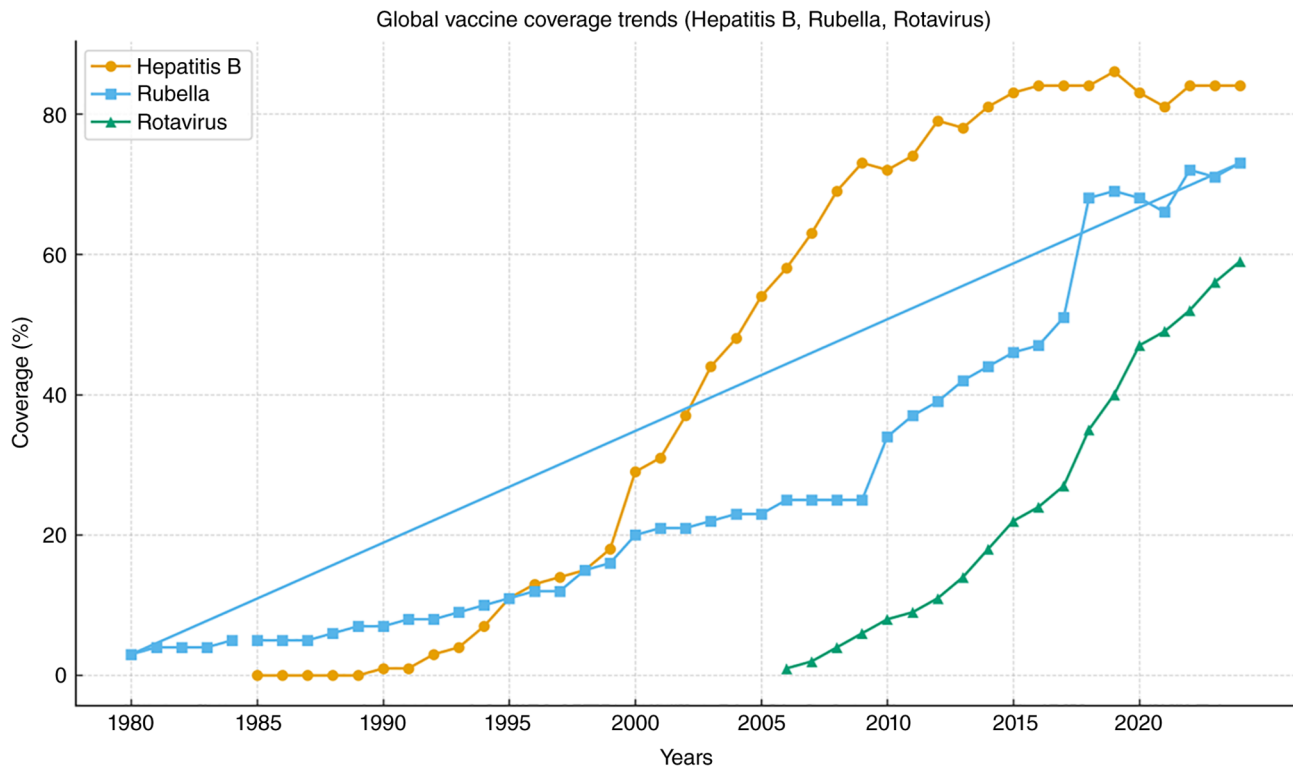


Figure 9. Global coverage of hepatitis B, rotavirus and rubella vaccines (1980-2024). Hepatitis B (3 doses): Global HepB3 coverage expanded from 0% in 1985 to ~84 in 2024, reflecting its universal inclusion in childhood immunization schedules since the early 2000s. Rotavirus: Introduced in 2006, global coverage increased rapidly from 1% (2006) to ~59% (2024), illustrating accelerated uptake following WHO recommendation and Gavi-supported programs. Rubella (1 dose): Global rubella (RCV1) coverage rose steadily from 3% in 1980 to ~71% in 2024, demonstrating long-term integration into the measles-rubella combined schedule. Sources: WHO/UNICEF Estimates of National Immunization Coverage (WUENIC, 2024); Our World in Data (2024).

after 2010. The growth trajectory demonstrates strong uptake in Africa and South-East Asia, regions historically burdened with high pneumococcal morbidity and mortality.

The health impact of pneumococcal vaccination has been profound (Fig. 10). In 2019 alone, PCV immunization was estimated to have averted almost 400,000 deaths globally, including ~275,000 in Africa and 92,300 in Asia, reflecting its critical role in reducing infant mortality in resource-limited regions (43). Conversely, Europe and North America reported <5,000 and 11,000 deaths averted, respectively, consistent with their earlier vaccine adoption and lower baseline disease prevalence. The cumulative effects of PCV vaccination since global introduction mirror the broader vaccine-driven decline in mortality highlighted in previous analyses (Figs. 2-9), underscoring how newer conjugate vaccines continue to expand the legacy of the EPI in saving millions of lives annually (21,30).

13. Impact of bacterial vaccination on global child health (1980-2024)

The combined impact of bacterial vaccines, including DTP3, Hib and pneumococcal conjugate vaccines, has been profound in reducing childhood morbidity and mortality worldwide. DTP3 coverage increased from 20% in 1980 to 84% in 2024, establishing one of the strongest pillars of global immunization and preventing >13 million deaths associated with *Bordetella pertussis*, *Corynebacterium diphtheriae*

and *Clostridium tetani* infections. The Hib vaccine, introduced globally in the early 1990s, expanded from near-zero coverage in 1990 to 78% by 2024 (Fig. 11). Its implementation was particularly transformative in low- and middle-income countries, where Hib previously represented a leading cause of bacterial meningitis and pneumonia in children <5 years of age.

Parallel progress was achieved with PCV3, introduced in the late 2000s. Global coverage increased from 4% in 2008 to 67% in 2024, averting ~399,000 deaths worldwide in 2019 alone, of which 275,000 occurred in Africa and ~92,000 in Asia. Together, these three vaccines account for most lives saved from bacterial infections from 1974-2024, as visualized in the global lives-saved analysis (Fig. 10). Across all bacterial pathogens, tetanus and pertussis rank among the top five in mortality reduction, while Hib and pneumococcal vaccination jointly contributed ~4.5 million prevented deaths since their introduction. The high and sustained coverage of these vaccines underscores their essential role in achieving Sustainable Development Goal 3.2, to end preventable deaths of newborns and children <5 years of age (21,22,30,41,42).

14. Global inequities and vaccine stock-outs (2022-2024)

Despite substantial progress being made in global immunization coverage, large disparities persist in vaccine access and continuity of supply. According to WHO/UNICEF and OWID estimates (21), 89 countries experienced stock-outs of at least one vaccine in 2022, with DTP-containing vaccines

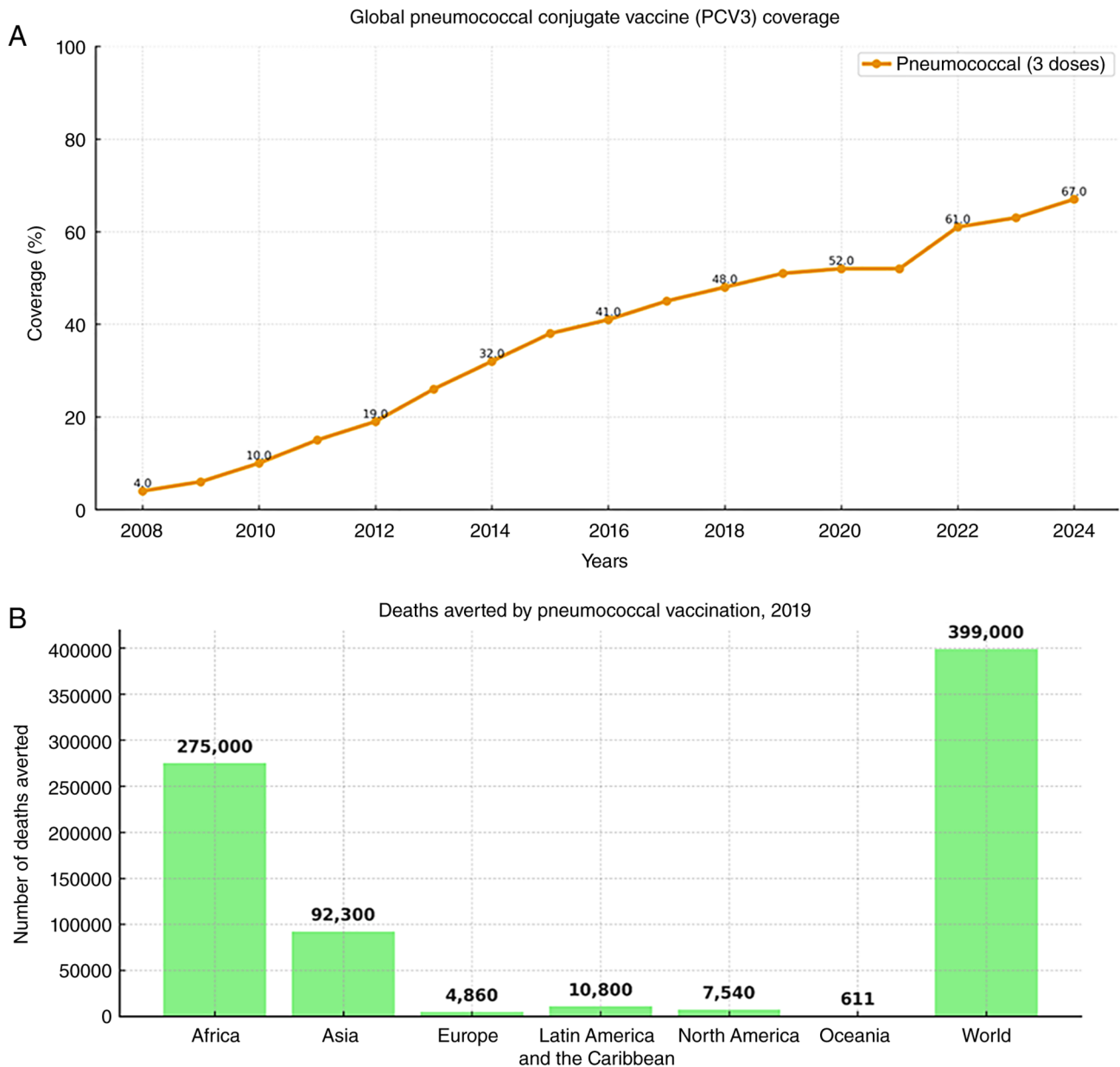


Figure 10. Global pneumococcal vaccination coverage and deaths averted (2008-2024). (A) Global increase in pneumococcal conjugate vaccine (PCV3) coverage among 1-year-old children, rising from 4% in 2008 to 67% in 2024 (WHO/UNICEF, 2024). (B) Deaths averted in 2019, with the highest impact in Africa (275,000) and Asia (92,300), underscoring the critical contribution of the vaccine to reducing childhood mortality in low- and middle-income regions (Our World in Data, 2024; WHO, 2024).

showing the highest disruption. BCG shortages were reported in 26 countries, measles-containing vaccine shortages in 25, and Hib-containing vaccine interruptions in 10. Even newer vaccines, such as PCV and rotavirus vaccines, faced shortages in 21 and 20 countries, respectively (Fig. 12). These interruptions undermine progress in routine immunization and leave millions of infants unprotected from preventable diseases.

The distribution of vaccine shortages reflects structural inequities and supply-chain vulnerabilities. The majority of affected countries are in sub-Saharan Africa and parts of South Asia, regions already burdened by weak cold-chain infrastructure, conflict-related disruptions, and delayed donor support. Conversely, high-income countries reported few or no stock-outs, maintaining consistent vaccine availability

through domestic production and diversified procurement systems. The persistence of these gaps underscores that global vaccine success is not uniform: While average global coverage for DTP3, Hib and PCV is >70%, in dozens of low- and middle-income countries, coverage remains <50% for at least one of these essential childhood vaccines.

Addressing these inequities requires strengthening regional manufacturing capacity, ensuring sustained funding through Gavi's 6.0 strategy (2021-2025), and integrating emergency response logistics with routine immunization programs. Without addressing vaccine shortages and distribution inequalities, global eradication and mortality reduction targets, such as those set under the Immunization Agenda 2030 (44), will remain unachievable (21,22,41,42).

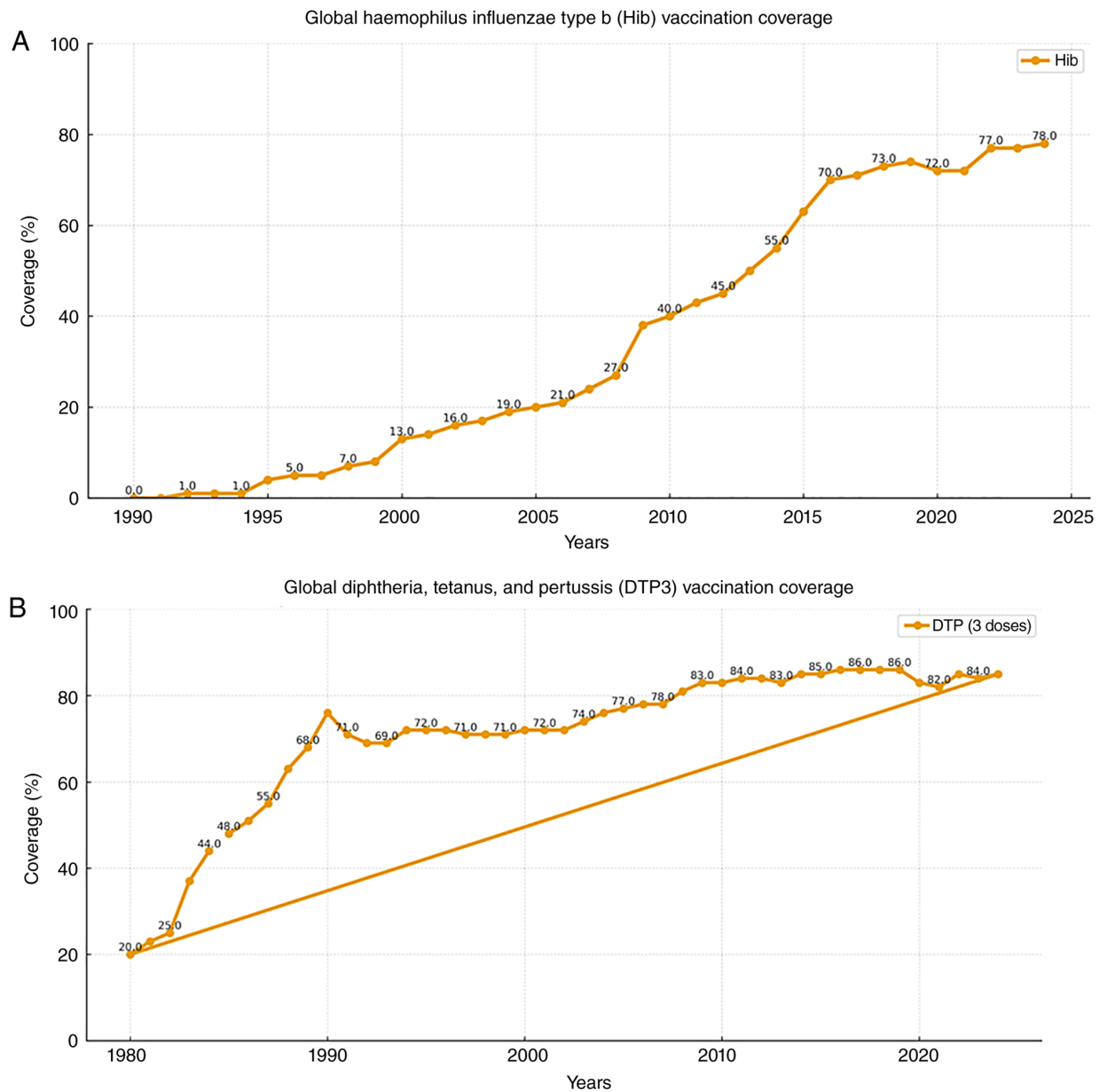


Figure 11. Global coverage of DTP3 and Hib vaccines (1980-2024). The figure illustrates global vaccination coverage trends for (A) *Haemophilus influenzae* type B (Hib) and (B) diphtheria-tetanus-pertussis (DTP3) among 1-year-old children, based on WHO/UNICEF 2024 revision estimates. Data points are labeled for alternate years, including the first and last data values, highlighting rapid coverage expansion since the 1990s and the stabilization of global routine immunization above 75% in recent years. Source: WHO/UNICEF Estimates of National Immunization Coverage (WUENIC 2024); Our World in Data (2024).

15. Overview

Over the past five decades, vaccination has transformed global health, preventing an estimated 150 million child deaths and reshaping disease patterns worldwide (21,22). Peer-reviewed studies have repeatedly confirmed vaccination as one of the most cost-effective health interventions, second only to clean water in reducing mortality and disability worldwide (2,45). Beyond its direct health benefits, vaccination has also contributed to improved life expectancy, reduced healthcare costs, and strengthened economic productivity by preventing large-scale disease outbreaks.

The evidence presented herein demonstrates the unparalleled impact of immunization on mortality decline, particularly in low- and middle-income countries. Global

coverage for DTP3, measles, polio and hepatitis B is currently >80%, compared with <20% in 1980 (WHO/UNICEF WUENIC, 2024) (15). These advances were driven by coordinated international efforts, most notably the EPI, Gavi, Vaccine Alliance and UNICEF, which established sustainable vaccine procurement, cold-chain systems, and community outreach in resource-limited settings (17,41,42). Additional contributing factors include improvements in health infrastructure, expanded maternal and child health services, stronger disease surveillance systems and increased international funding mechanisms supporting routine immunization programs.

The greatest absolute benefits were observed in Africa and South-East Asia, regions accounting for almost 70% of global lives saved. These regions historically experienced the highest

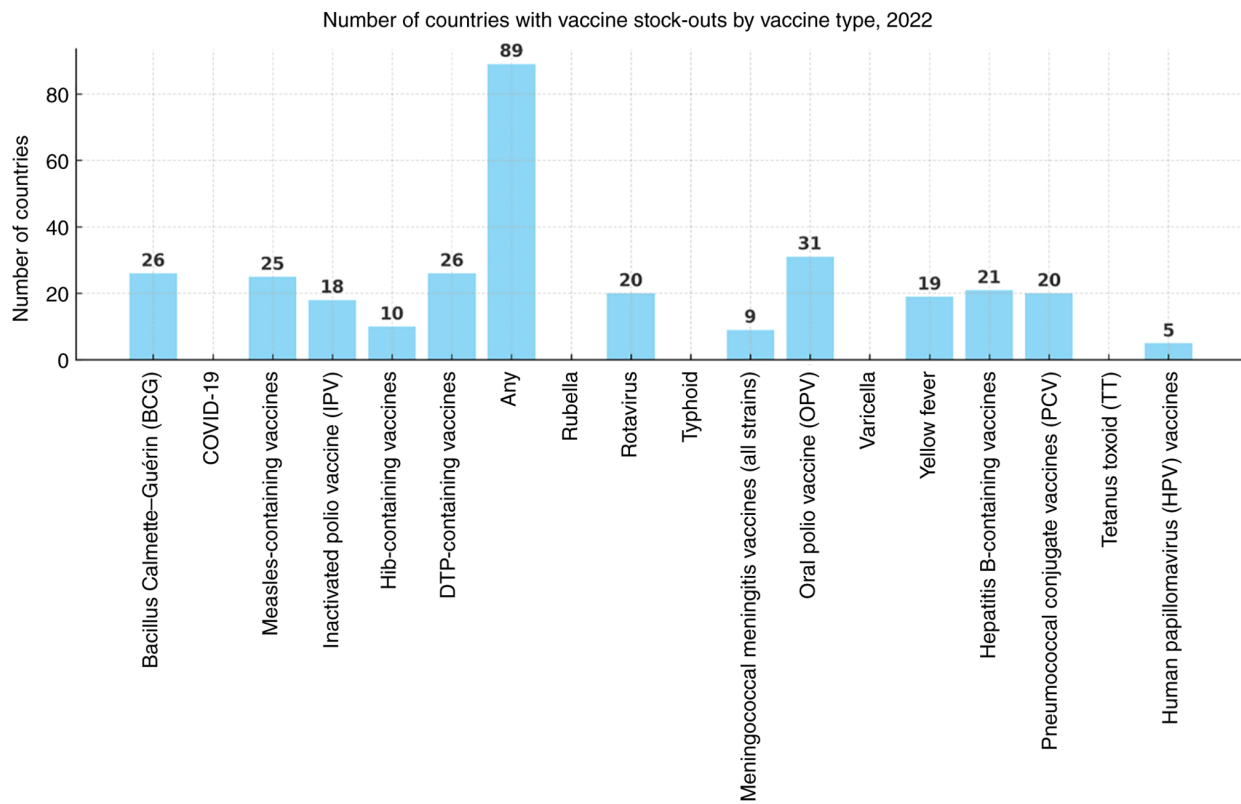


Figure 12. Number of countries with vaccine stock-outs by vaccine type, 2022. The figure illustrates the number of countries that experienced national vaccine shortages (stock-outs) across 17 vaccine types in 2022, based on WHO/UNICEF and Our World in Data reports. The most frequent stock-outs occurred for DTP-containing vaccines (89 countries) and Bacillus Calmette-Guérin (BCG) vaccine (26 countries), followed by measles and rubella vaccines (25 and 20 countries, respectively). These shortages highlight persistent global inequities in vaccine supply and access, particularly in low- and middle-income countries (LMICs). Source: WHO/UNICEF (WUENIC, 2024); Our World in Data (Vaccination Dataset, 2024).

burden of VPDs, meaning that the expansion of immunization programs resulted in proportionally larger health gains. Independent global modelling analyses have shown that immunization programs have averted >50 million deaths since 2000, with measles and hepatitis B vaccination contributing the largest proportion of lives saved (44,46). Measles-related deaths declined from 2.6 million in 1950 to 73,000 in 2021, while smallpox eradication in 1980 and a >99% reduction in poliomyelitis incidence illustrate the power of sustained global coordination (20). More recent introductions, pneumococcal, rotavirus, Hib and hepatitis B vaccines, further reduced childhood mortality, with pneumococcal immunization alone preventing ~400,000 deaths in 2019 (22,35). Collectively, bacterial (DTP, Hib and pneumococcal) and viral vaccines (measles, polio, rubella, rotavirus and hepatitis B) currently prevent millions of deaths annually and significantly contribute to the decline of mortality rates in children <5 years of age globally. These findings demonstrate how continuous innovation in vaccine development and expansion of immunization schedules have strengthened global disease prevention strategies.

Despite these achievements however, substantial inequities persist. Recent analyses highlight widening gaps in vaccine access across socioeconomic and geographic lines, with fragile and conflict-affected states accounting for >40% of under-immunized children worldwide (47-49). These disparities are often associated with limited healthcare infrastructure, economic constraints, political instability, population

displacement and difficulties in maintaining reliable vaccine supply chains. As demonstrated in recent WUENIC and OWID analyses, 89 countries reported vaccine stock-outs in 2022, with the highest shortages affecting DTP-containing and BCG vaccines (21,22). These disruptions, largely concentrated in sub-Saharan Africa and South Asia, reflect systemic weaknesses in supply chains, financing and conflict-affected health systems. They threaten to reverse decades of progress, particularly following the COVID-19 pandemic, which interrupted routine immunization in >100 countries (41). Addressing these challenges will require strengthening national immunization programs, improving supply-chain resilience and enhancing international collaboration to support vulnerable health systems.

Sustaining global progress will require targeted investments to strengthen manufacturing capacity, expand regional vaccine production and ensure timely delivery in fragile contexts (42). Emerging literature emphasizes that resilient immunization systems depend on not only financing and logistics but also community trust and misinformation control, key predictors of post-pandemic vaccine recovery (50,51). Community perceptions regarding vaccine safety have also influenced vaccination uptake and recovery after the COVID-19 pandemic. A regional study in Sudan reported that concerns about vaccine side-effects significantly affected willingness to receive COVID-19 vaccines, highlighting the importance of public awareness and trust in immunization programs (52). These findings reinforce that addressing safety

concerns and improving risk communication are essential for restoring vaccination coverage after pandemic-related disruptions. Public health strategies should therefore also focus on community engagement, transparent communication, and the combatting of vaccine misinformation to improve vaccine acceptance and coverage.

Emerging advances in molecular diagnostics and biomarker discovery may further strengthen vaccine research and public-health surveillance in the future. For example, studies investigating miRNA expression profiles in complex conditions such as polycystic ovary syndrome demonstrate how molecular biomarkers can improve disease detection and monitoring. These technologies could potentially support vaccine safety evaluation and maternal-child health surveillance by enabling earlier detection of immune responses and adverse events (53).

The integration of immunization with primary healthcare services and digital tracking systems could further reduce drop-outs and inequities. The Immunization Agenda 2030 (44) emphasizes reaching the 'zero-dose child' and achieving equitable access across all populations, goals achievable only through sustained political commitment, adequate funding, and public trust (22). Vaccination has already rewritten the history of infectious diseases; maintaining this trajectory demands that no child, regardless of geography or income, be left unprotected.

The present review study has several limitations, which should be mentioned. These are related to the use of secondary global datasets. First, vaccination coverage and disease burden estimates rely on surveillance systems and administrative reporting, which may vary in completeness and accuracy across countries, particularly in low- and middle-income regions where underreporting and gaps in surveillance remain common. Second, estimates of deaths averted are based on modelled counterfactual scenarios rather than direct measurements, meaning results depend on assumptions used in epidemiological models such as those from the GBD and WHO datasets. Third, differences in case definitions, reporting systems, and historical data availability may introduce bias when comparing long-term trends across decades. Finally, disruptions to routine immunization during the COVID-19 pandemic may have temporarily affected vaccination coverage and surveillance accuracy, potentially influencing recent estimates of vaccine impact.

16. Conclusion and future perspectives

Vaccination has been one of the greatest triumphs in the history of medicine, saving an estimated 150-160 million lives and preventing countless disabilities worldwide since the mid-20th century. Global immunization efforts have led to the eradication of smallpox (1980) and the elimination of rinderpest (2011), while polio, measles and neonatal tetanus are approaching eradication in the majority of regions. The EPI, established by the WHO in 1974, together with UNICEF, Gavi and IHME-led monitoring, has expanded vaccine coverage to >90% of children worldwide. However, gaps remain: Of note, ~20 million infants each year still miss basic vaccines, and vaccine hesitancy, conflict and inequitable access continue to pose major global threats. Sustaining political commitment, strengthening local manufacturing, and integrating novel technologies such as mRNA platforms and thermostable formulations are crucial

for achieving the Immunization Agenda 2030 goals. Ensuring that no population is left behind will be key to preventing the re-emergence of preventable diseases and protecting the remarkable progress of the past 70 years.

However, the present review study relied primarily on secondary data from global databases, which may include variations in reporting quality and completeness across countries and time periods. Future research should focus on more detailed country-level analyses and the evaluation of strategies to reduce vaccination inequalities and strengthen immunization systems worldwide.

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Author's contributions

TAHS conceptualized and designed the study, performed the literature review, and drafted the manuscript.

Ethics approval and consent to participate

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Patient consent for publication

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Competing interests

The author declares that he has no competing interests.

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