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Assessing the impact of heat waves on childhood immunization coverage in Sindh, Pakistan: Insights from 132.4 million doses recorded in the provincial electronic immunization registry (2018–2024)

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ABSTRACT

Introduction: Heat waves, intensified by climate change, are increasingly challenging health systems, particularly in low- and middle-income countries (LMICs). Pakistan, ranked among the top 10 most climate-vulnerable nations, faces significant challenges in maintaining routine immunization coverage rates amid soaring temperatures. This study examines the impact of heat waves on immunization delivery in Sindh Province of Pakistan, a region highly vulnerable to climate-induced disruptions.

Methods: We analyzed child-level data from the provincial electronic immunization registry for 132.4 million immunization doses administered between January 1, 2018, to July 31, 2024. We used the clustered panel univariate and multivariable Poisson and negative binomial regressions to analyze the association between high temperature alert days (33 °C to 39.9 °C) and heat waves (> 40 °C) and immunizations, by vaccination modality (fixed site, routine outreach, enhanced outreach). The analysis controlled for external shocks, such as floods, the COVID-19 pandemic, and vaccinators' strikes, and accounted for geographic and temporal variation.

Results: Heat waves and high temperature alert days (≥33 °C) significantly reduced immunizations, with routine and enhanced outreach activities being most affected (13.6 % and 21.2 % decline respectively). Fixed-site immunizations witnessed a comparatively lower decline i.e. 5.8 %. Rural Divisions Larkana and Sukkur were disproportionately affected, while Karachi exhibited minimal impact. Despite the negative impact of heat waves, immunization efforts intensified during external shocks like floods and the COVID-19 pandemic, particularly through prolonged and frequent outreach activities.

Discussion: Heat waves disrupted vaccine service delivery leading to reduced immunization coverage in Sindh, disproportionately affecting immunizations administered through outreach activities. Geographic and temporal variations highlight the need for localized strategies, including improved infrastructure, optimized outreach schedules, and robust vaccine cold chains. Future research should explore long-term adaptive strategies for maintaining vaccination coverage amid increasing impact of climate change, especially in low-resource settings.

1. Introduction

Climate change is increasingly recognized as one of the most significant global threats of the 21st century [1] due to the intensification of extreme weather events such as heat waves, floods, droughts, hurricanes, cyclones, rise in sea level, and heavy and prolonged precipitation [2]. Over the past few years, deadly heat waves (defined as "a period where local excess heat accumulates over a sequence of unusually hot

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days and nights" [3] have ravaged the globe, claiming thousands of lives [4] and posing serious threats to public health systems and services. A growing body of evidence demonstrates that extreme weather events, such as heat waves increase the spread and frequency of transmissible infectious diseases, impacting over half of the world's 375 major contagious diseases and posing substantial risks to highly vulnerable populations in disaster-prone areas [5]. The debilitating effects of heat waves, therefore, have far-reaching implications for the control of infectious diseases and preventable illnesses.

Investigating the impact of heat waves on routine immunization services is critically important, particularly as projections suggest that global warming and rising regional temperatures will intensify [6] in the coming years. However, these disruptions will not affect all regions equally. Countries marked with high geographic exposure, dense population, and socioeconomic challenges are disproportionately more vulnerable. In such settings, heat waves exert substantial pressure on public health systems, especially where infrastructure is fragile. The World Health Organization [7] emphasizes that rising temperatures, including more frequent and intense heat waves, threaten to overwhelm health systems and increase mortality, calling for urgent action to strengthen health infrastructure and improve climate resilience. These challenges are further compounded by limited access to essential resources such as electricity, clean water, reliable transportation, and resilient supply chains [8]. Pakistan ranks among the top 10 countries most affected by climate-related events, including heat waves. [9]. The country has experienced temperature increases that exceed the global average, a risk further amplified by its demographic and socioeconomic context. Sindh province, located in the south region of the country, in particular, has experienced a sharp rise in both the frequency and intensity of heat waves [6], positioning it as a critical area for understanding the impacts of climate change on health services.

Despite improvements in fully immunized child (FIC) coverage for Sindh from 25 % in 1990–91 to 49 % in 2018 [10] these gains remain fragile as the increasing threat of heat waves can disrupt immunization services, potentially reversing tthis progress. Literature suggests that extreme heat can disrupt vaccination in multiple ways, primarily by affecting the vaccine cold chain, service delivery, and access. As sensitive biological products, vaccines are vulnerable to heat exposure, which can shorten their shelf life, and limit their effectiveness [11]. Moreover, extreme heat can impede the delivery of immunization services by limiting the mobility of healthcare workers, who may face challenges traveling in severe weather conditions, particularly in rural or remote areas [12]. In addition, heat waves can limit users' access to healthcare centers [13], which may be forced to close or operate at reduced capacity due to infrastructural damage. These heat-related barriers disproportionately affect vulnerable populations and further strain already fragile health systems, hindering efforts to control vaccine-preventable diseases (VPDs) [14]. Although the impact of heat waves on public health is increasingly recognized, there is limited quantifiable evidence on how extreme temperatures specifically affect immunization systems in low- and middle-income countries (LMICs) [7]. Moreover, current research primarily focuses on the immediate health consequences of heat waves, such as heat stroke and other heat-related illnesses, rather than the disruptions on health services like immunization programs. Additionally, there is a notable lack of published studies on the impact of heat waves on immunization services from countries with geographic, socioeconomic, and demographic characteristics similar to Pakistan despite these regions' heightened vulnerability to both climate change and public health challenges. The absence of such research creates a significant barrier to the development of effective strategies aimed at fortifying immunization services and ensuring their resilience amidst rising global temperatures. Addressing this gap is crucial for safeguarding public health in LMICs as climate change-related disruptions continue to intensify.

Our study aims to address this gap by analyzing the impact of heat waves on routine immunization services in Sindh province, Pakistan. We specifically assess how heat waves affect the number of immunization doses administered through fixed-site facilities and outreach vaccination activities across the province, while examining geographic and temporal variations. Given that fixed-site immunizations depend on caregivers visiting healthcare centers, and outreach activities require vaccinators to travel to communities, each approach encounters distinct challenges during extreme heat events. By identifying these patterns, our study seeks to offer insights into how heat waves disrupt different modes of vaccine delivery and the implications for immunization coverage in Sindh province and other similar settings.

2. Methods

2.1. Population and setting

Sindh province, located in southern Pakistan, has a population of 55.7 million [15] and an annual birth cohort of approximately 2.0 million based on a total fertility rate of 3.6 % [16], with a population density of 395.25 people/sq. Km [15]. Administratively, it is divided into six divisions: Karachi, Hyderabad, Sukkur, Larkana, Shaheed Benazirabad, and Mirpurkhas. The divisions are further subdivided into 30 districts, 142 towns, and 1120 union councils (UCs; the smallest geographic administrative unit) [17]. Of these, 8 are classified as super high-risk UCs (SHRUCs), areas endemic to polio that present the highest risk due to densely populated, underserved communities with low polio vaccination coverage [18].

According to a survey conducted in 2020, Sindh's FIC coverage was 61.1 %, below the national immunization coverage of 76.4 %. The highest coverage was for Bacillus Calmette-Guerin (BCG) (91.9 %), with coverage rates decreasing for vaccines administered later in the WHO recommended immunization schedule (Penta-3: 73.2 % and Measles-1: 67.1 %) [19].

The province employs a multifaceted immunization strategy, incorporating fixed sites, routine outreach activities (ROAs), and enhanced outreach activities (EOAs) [20]. ROAs involve holding immunization sessions at sites outside the main centers, allowing vaccinators to travel to and from the location within the same day. EOAs, however, consist of multiple sessions aimed at reaching areas that fall outside the usual coverage of routine efforts. Traditionally, fixed sites provided 60 % of immunizations, but post-COVID-19, this proportion has decreased to 40 %, with 60 % immunizations being administered at outreach sites [21]).

The province frequently experiences extreme heat, with a predominantly hot and arid to humid climate. Summers, from May to August, are particularly intense, with daytime temperatures often exceeding 50°C [22]. Most regions of Sindh, including Nawabshah, Larkana, Jacobabad, Hyderabad, Karachi, Chhor, and Padidan, experience extreme heat conditions during the summer months. These areas are particularly vulnerable to heat-related illnesses, such as heatstroke and sunburn, especially during the peak hours of the day. The remaining regions of Sindh, while still experiencing high temperatures, are generally within tolerable limits for the local population (supplementary fig. 1).

In recent years, the frequency and duration of heat waves have increased, likely due to climate change [22]. In May 2024, temperatures rose noticeably in Sindh, with higher minimum and maximum temperatures in June and July. Hyderabad, Larkana, and Sukkur were the hottest divisions (supplementary fig. 2). These heat events elevate health risks, particularly for vulnerable populations [23], and contribute to water shortages, damaged crops, and frequent power outages [24].

2.2. Vaccination schedule

The EPI in Pakistan aims to safeguard children against ten VPDs, including tuberculosis, polio, diphtheria, tetanus, pertussis, *Haemophilus influenzae* type b, hepatitis b, pneumococcal infections, rotavirus diarrhea, and measles through a series of six scheduled visits. At birth, children receive the BCG vaccine and the birth dose of oral polio vaccine

(OPV). At six weeks of age, they are administered the initial doses of pentavalent, pneumococcal conjugate vaccine (PCV), rotavirus vaccine, and OPV. Additional doses of these vaccines are provided at 10 and 14 weeks, with the inactivated polio vaccine (IPV) introduced at 14 weeks. At nine months, children receive the first Measles-Rubella vaccine, the Typhoid conjugate vaccine (TCV), and a second IPV dose. A second dose of the measles vaccine is given at 15 months.

2.3. Data sources

We extracted the individual immunization records of all children vaccinated from January 1, 2018 to July 31, 2024 across Sindh Province, Pakistan, using the provincial EIR, also known as the Zindagi Mehfooz (Safe Life) ElR (ZM-EIR) to determine the study outcomes. The timeframe for data analysis was selected because the provincial EIR, our primary data source, was fully scaled across all districts of Sindh by early 2018, enabling consistent and uniform data availability. The cutoff date of July 31, 2024 was chosen to accommodate data cleaning and ensure analytical completeness prior to data analysis.

The provincial EIR is a real-time, low-cost digital platform designed to strengthen routine immunizations. It enables real-time recording of child immunization data at the individual level, web-based monitoring, and provides granular data that supports data-driven decision-making, helping health officials optimize outreach, resource allocation, and policy planning [25]. The provincial EIR operates via Android-based smartphones, enabling vaccinators to enroll children aged 0–23 months at their first immunization visit and to track subsequent doses on follow-ups. The registry captures comprehensive information, including child demographics, vaccination details, health facility and vaccinator identifiers, and geolocation of vaccine doses. Each child is assigned a unique identifier, allowing for continuous record linkage and performance monitoring. Initially piloted in 2012, the system was formally scaled across the Sindh province beginning in October 2017, laying the groundwork for province-wide digital immunization tracking under the provincial EIR framework [26]. More details on the registry, description of data captured through the registry and an evaluation of the system have been published elsewhere [20,25–28].

The daily climate data for the analysis was obtained from Custom Weather [29].

2.4. Outcomes

The primary outcome measure was to assess the impact of heat waves on the total number of immunizations administered through fixed sites and outreach activities. We calculated the total number of immunizations by adding the vaccines administered through each vaccination modality (fixed sites, ROA and EOA) during both, periods of heat waves and routine temperatures, covering the full series of routine childhood vaccinations. We defined heat waves as the days when the heat index (feels like temperature) reached or exceeded 40 °C, in accordance with the National Disaster Management Authority's (NDMA) official guidance [30]. In addition, days with heat index values ranging from 33 °C to 39.9 °C were classified as high-temperature alert days due to their potential to contribute to cumulative heat stress, particularly among vulnerable populations. This framing clarifies that 40 °C is the operational threshold for defining a heat wave, while 33–39.9 °C denotes elevated heat that, although not classified as a heat wave, remains epidemiologically relevant. These definitions align with the NDMA's early warning categories, including alert-level and heat wave-level classifications and were adopted to ensure methodological consistency with national climate risk framework [30].

We controlled for external shocks that could influence immunization activities, including floods, the COVID-19 pandemic, and vaccinators' strikes. Geographical variability across districts was also accounted for in the analysis.

We also compared the average immunizations during heat waves versus routine periods across the six administrative divisions in Sindh province. To assess temporal trends in immunizations during heat waves compared to the routine periods, we examined yearly fluctuations in the mean immunizations administered across the 30 districts within these six divisions. Additionally, we compared changes in temperature during the summer months over the years to assess seasonal variability.

2.5. Statistical analysis

We calculated the heat index using the Lans P. Rothfusz formula [31]. For analysis, the heat index (HI) was categorized into different categories: tolerable (<33 °C), caution (≥33 °C), caution/extreme caution (<40 °C), and danger (≥40 °C) and further classified into four health related-levels: tolerable <33 °C, caution/extreme caution (33–39 °C), danger (40–53 °C) and extreme Danger (≥54 °C) [30,32].

We employed clustered panel univariate and multivariable Poisson and negative binomial regressions to examine the factors associated with the total number of vaccinations administered through fixed sites, ROAs and EOAs after controlling for external shocks (floods, vaccinators strike, COVID-19 pandemic). The overdispersion assumption for Poisson regression was assessed using the overdispersion parameter (alpha). Therefore, negative binomial regression was applied. The model with the lowest AIC value was considered the final multivariable model. All tests were two-sided, and statistical significance was set at 0.05. Statistical analyses were performed with Stata, release 17 (StataCorp, College Station, TX).

Bar graphs were used to compare the total mean number of immunizations administered during the low and high heat index periods across different divisions and years. The total mean number of immunizations were calculated by determining the mean number of immunizations administered on days with low and high heat indexes for each district and year. These district-level means were then summed to represent the total mean number of immunizations for each division or year. Additionally, average, minimum, and maximum temperatures during summer (May–September) by year and division are presented as range plots with capped spikes.

We performed geospatial analysis using QGIS 3.34.1. Aggregated at the district level, vaccination data was overlaid with heat wave occurrence data to identify spatial patterns and variations in immunization rates under both, routine temperatures and heat wave conditions.

2.6. External shocks

Floods: In 2022, Pakistan faced devastating floods, primarily triggered by unprecedented monsoon rains that persisted from July through October. These extreme rains were a direct consequence of climate change, with scientists estimating that the intensity of rainfall was up to 75 % higher than it would have been without human-induced global warming [33]. Sindh was the most affected province, with 24 districts officially declared calamity hit, bearing approximately 70 % of the total province-wide losses and damages. The floods affected millions, causing widespread destruction to homes, infrastructure, and farmlands, resulting in significant loss of life, mass displacement, and a humanitarian crisis with long-term impacts on the economy, agriculture, and public health [34,35].

Vaccinators strike: In 2020 (June 12–July 16) and 2021 (February 26–May 3 and November 1–December 11), vaccinators in Sindh staged multiple strikes, which disrupted the routine immunization service across the province [36].

COVID-19 pandemic: The COVID-19 pandemic, declared as a Public Health Emergency of International Concern (PHEIC) by the WHO on January 30, 2020 [37], had a prolonged impact on public health. Routine immunization programs were significantly disrupted, with approximately 50 % of children in Sindh province missing their scheduled vaccinations during the provincial lockdown [38].

2.7. Ethical approval

The Institutional Review Board at Interactive Research and Development determined this analysis to be exempt, in line with the criteria outlined in 45 CFR 46.101(b). The IRB is registered with the U.S. Department of Health and Human Services Office for Human Research Protections under registration number IRB 40400005148.

2.8. Role of the funding source

This work was supported by grants from GiveWell, Gavi, the Vaccine Alliance and Gates Foundation, to enhance the immunization programme in Sindh, Pakistan. The funders had no role in study design, data collection, data interpretation or report writing.

3. Results

3.1. Geographical and Temporal Variation in the Impact of Heat Waves on Immunization Doses

A total of 132.4 million immunization doses were administered to 10.9 million children vaccinated through the provincial EIR across Sindh Province, Pakistan, from January 1, 2018, to July 31, 2024. The total number of immunizations administered increased from 6.8 million in 2018 to a peak of 30.6 million in 2023. The corresponding figures for 2019, 2020, 2021, 2022 and 2024 were 11.5 million, 18.5 million, 19.5 million, 29.2 million, and 16.3 million respectively (data not shown).

Fig. 1 compares the total average immunization doses administered during the HI ≥ 33 °C and HI < 33 °C period (panel A) and HI ≥ 40 °C and HI < 40 °C (panel B) across the six divisions of the province. The average immunization doses in the HI ≥ 33 °C and HI ≥ 40 °C decreased across all the divisions compared to the duration when HI was below 33 °C and 40 °C (decrease between HI ≥ 33 °C and HI < 33 °C ranging from 3.5 to 13.6 % and decrease between HI ≥ 40 °C and HI < 40 °C ranging from 2.5 to 10.7 %). The highest drop was observed in Larkana division (HI ≥ 33 °C 13.6 % & HI ≥ 40 °C: 10.7 %), followed by Sukkur division (HI ≥ 33 °C: 12.4 % & HI ≥ 40 °C: 8.3 %). Karachi division experienced the lowest decline (HI ≥ 33 °C: 3.5 % & HI ≥ 40 °C: 2.5 %).

Fig. 2 shows the temporal analysis for the same comparison, across the years 2018–2024. In 2018, a higher number of average immunization doses were administered during periods of lower heat index (HI) compared to higher heat index periods. When the HI was <33 °C, immunizations were 6.6 % higher than when HI was ≥33 °C (21,752 vs. 20,400 during HI ≥33 °C), and when the HI was <40 °C, they were 11.9 % higher compared to HI ≥ 40 °C (22,329 vs. 19,957 during HI ≥40 °C). In contrast, in 2019, the trend reversed, with more doses administered during periods of higher heat index. Immunizations were 25.8 % higher during HI ≥33 °C compared to when the HI was <33 °C (37,692 vs. 29,969) and 25.5 % higher during HI ≥40 °C compared to when the HI was <40 °C (38,237 vs. 30,469). In 2020, a significant increase in the average number of immunization doses was observed during periods of lower heat index compared to higher heat index periods. When the HI was below 33 °C, immunizations were 33.1 % higher (71,442 vs. 53,666 during HI ≥33 °C), and when the HI was below 40 °C, immunizations were 27.6 % higher (68,038 vs. 53,324 during HI ≥40 °C). A similar trend was observed in 2021, with 51 % higher immunizations during HI <33 °C (82,674 vs. 54,753 during HI ≥33 °C) and 33.7 % higher during HI <40 °C (74,111 vs. 55,425 during HI ≥40 °C). In contrast, during 2022 and 2023, a higher average number of doses were administered during periods of higher heat index, suggesting enhanced vaccination efforts during heat waves. In 2022, doses were 3.0 % higher during HI ≥33 °C (85,905 vs. 83,406 during HI <33 °C) and 4.1 % higher during HI ≥40 °C (86,635 vs. 83,251 during HI <40 °C). Similarly, in 2023, doses were 3.0 % higher during HI ≥33 °C (90,877 vs. 88,228 during HI <33 °C) and 4.4 % higher during HI ≥40 °C (91,872 vs. 87,967 during HI <40 °C). In 2024, up until July, the trend reversed again, with more immunizations administered during lower heat index periods. When the HI was below 33 °C, immunizations were 9.2 % higher (87,591 vs. 80,220 during HI ≥33 °C), and during HI <40 °C, immunizations were 9.4 % higher (86,724 vs. 79,252 during HI ≥40 °C).

From 2018 to 2024, the total number of immunizations increased during both low and high heat index periods (Fig. 3). However, the maps reveal notable differences in the mean number of immunizations administered during the low heat index period compared to the high heat index period. These differences were especially pronounced in 2020 and 2021, where a considerable reduction in immunization doses was observed when the heat index was high.

In 2022, while the average immunizations improved across most districts during the high heat index period compared to the low heat index period, a decrease was observed in Khairpur, Shikarpur, and Thatta districts. Whereas, in 2023, the average immunization increased across all the districts when the heat index was high. In 2024 (till July), the trend shifted again, with more immunizations administered during low heat index periods compared to high heat index periods across all districts, mirroring the pattern seen in Fig. 3.

3.2. Impact of heat waves on immunization doses by vaccination modality

During days when the heat index reached 33 °C or higher, total immunizations administered at fixed sites decreased by 5.8 % (IRR: 0.942; 95 % CI: 0.930–0.945, $p < 0.001$) compared to days with a heat index below 33 °C, after adjusting for external shocks and districts.

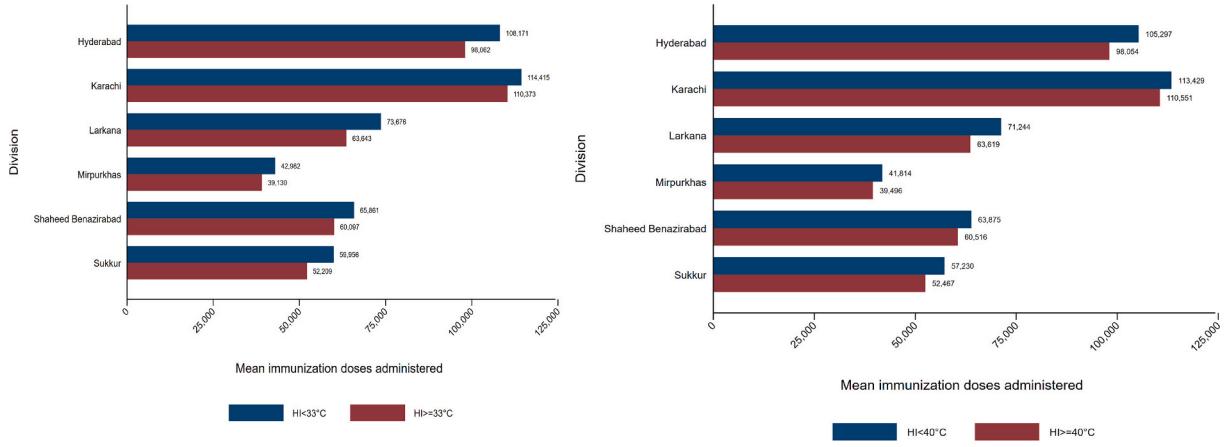

Fig. 1. Comparison of total mean immunization doses administered during low and high heat index periods each year in Sindh Province, Pakistan, by divisions, January 1, 2018-July 31, 2024.

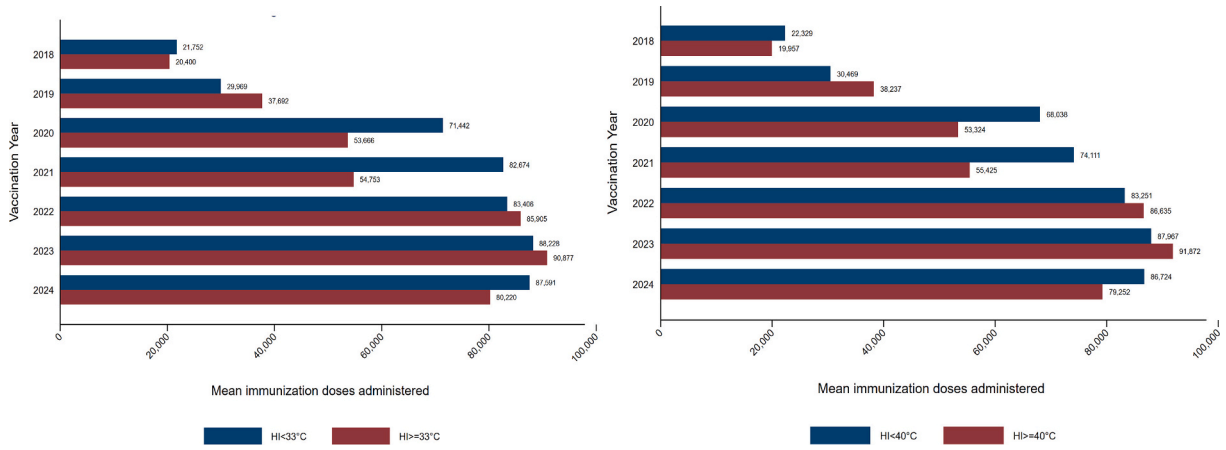

Fig. 2. Comparison of total mean immunization doses administered during low and high heat index periods across six divisions in Sindh Province, Pakistan, by year, January 1,2018-July 31, 2024.

Outreach activities, particularly EOAs, were more significantly affected by heat waves, with ROAs showing a 13.6 % decrease (IRR: 0.864; 95 % CI: 0.850–0.878, $p < 0.001$) and EOAs a 21.2 % decrease (IRR: 0.788; 95 % CI: 0.930–0.945, $p < 0.001$) when the heat index rose to 33 °C or higher (Model 1, Tables 1–3).

Furthermore, immunizations administered through fixed sites dropped by 6.1 % (IRR: 0.939; 95 % CI: 0.928–0.951, $p < 0.001$), ROA by 15.1 % (IRR: 0.849; 95 % CI: 0.837–0.861, $p < 0.001$), and EOAs by 22.7 % (IRR: 0.773; 95 % CI: 0.748–0.799, $p < 0.001$) on days when the heat index reached the danger level (≥40 °C) compared to days with a heat index below 40 °C, after adjusting for external shocks and districts (Model 2, Tables 1–3).

Breaking down the data further by categorizing the heat index into four health-related levels, there was a significant decrease of 8.5 % in total immunizations administered through fixed sites (IRR: 0.918; 95 % CI: 0.904–0.931, $p < 0.001$) on days when the heat index reached extreme danger levels (≥54 °C), and 3.5 % (IRR: 0.975; 95 % CI: 0.959–0.991, $p < 0.002$) and danger (40–53 °C) levels, compared to days with a tolerable heat index (<33 °C). A more pronounced decline was observed in immunizations administered through ROAs and EOAs during days when the heat index reached extreme danger (≥54 °C), with decrease of 20 % (IRR: 0.800; 95 % CI: 0.786–0.815, $p < 0.001$) and 28.7 % (IRR: 0.713; 95 % CI: 0.687–0.740, $p < 0.001$), respectively, and danger (40–53 °C) levels, with decrease of 6.4 % (IRR: 0.939; 95 % CI: 0.928–0.951, $p < 0.001$) and 5.4 % (IRR: 0.946; 95 % CI: 0.905–0.988, $p = 0.012$), respectively, compared to days with a tolerable heat index (<33 °C) (Model 3, Tables 1–3).

Moreover, during the floods, the total number of immunizations administered through ROAs increased by 65.0 % (IRR: 1.650; 95 % CI: 1.606–1.695, $p \leq 0.001$) compared to 6.2 % (IRR: 1.062; 95 % CI: 1.035–1.090, $p \leq 0.001$) through fixed sites adjusting for other variables. No EOAs were conducted during the flood period. The COVID-19 pandemic was also associated with an increase in immunizations, with IRRs ranging from 1.064 to 1.438 ($p < 0.001$), indicating improved immunization efforts during the pandemic and floods. Additionally, a sharp drop in total immunizations administered through all three modalities was observed during the vaccinator strikes, with IRRs ranging from 0.510 to 0.698 ($p < 0.001$).

4. Discussion

Our findings confirm that heat waves have a disruptive effect on routine childhood immunization, with outreach services being more adversely affected than fixed-site facilities. The decline in immunizations was most evident in 2020 and 2021 with immunizations declining up to 50% as temperatures increased. While elevated heat index values were generally associated with reduced immunization activity, this pattern was not consistent across all years. In 2019, 2022, and 2023, immunizations either remained stable or increased during periods of high heat, warranting more in-depth investigations. These exceptions suggest that other factors such as targeted campaigns, improved field planning, or community demand may have helped sustain service delivery despite unfavorable weather conditions.

The detrimental effects of heat waves on immunization services observed in our study align with growing evidence and caution from global entities such as the WHO, emphasizing how extreme weather negatively affects health services in LMICs [7,39]. For example, a study conducted in India, reported that exposure to natural disasters caused by climate change reduced the likelihood of achieving full age-appropriate immunization coverage by nearly 18 % [40]. Another study from Bangladesh observed that drought was associated with lower odds of completion of childhood BCG, DPT, and polio vaccinations [41]. However, despite this expanding body of literature on climate change impacts, there is limited research specifically examining the relationship between heat waves and vaccination outcomes. To the best of our knowledge, this is the first study to assess and quantify the association between heat waves and immunization, and the findings warrant more focused studies in the domain of climate-health interaction.

The association between extreme temperatures and lower immunization rates, specifically for outreach services may be explained by several mechanisms, including greater exposure of health workers, difficulty maintaining cold chain logistics, and inadequate essential infrastructure. During outreach, health workers in Pakistan, like other LMICs, travel to remote or underserved areas where infrastructure is less robust and environmental conditions are harsher [42] either on foot or on motorcycles or bicycles. The suboptimal transport mechanisms expose them directly to extreme heat, often putting them at risk of heat-related illnesses such as heatstroke and dehydration and lowering their overall productivity. Additionally, the physical strain on healthcare workers is coupled with cold chain disruptions and power outages, further impairing the effectiveness of outreach efforts [42]. These findings align with the broader literature on the effects of climate change on health services in LMICs. A study in Bangladesh reported that extreme weather events, such as heat waves, can cause disruptions to communication and transportation networks, reducing access to healthcare, especially in rural areas [43].

We observed certain geographic and temporal variations in the impact of extreme heat on immunization doses. Geospatial analysis revealed regional disparities in the impact of heat waves on immunization services across Sindh Province. Divisions such as Larkana and Sukkur experienced the most significant declines in immunization coverage during heat waves, whereas Karachi exhibited the smallest

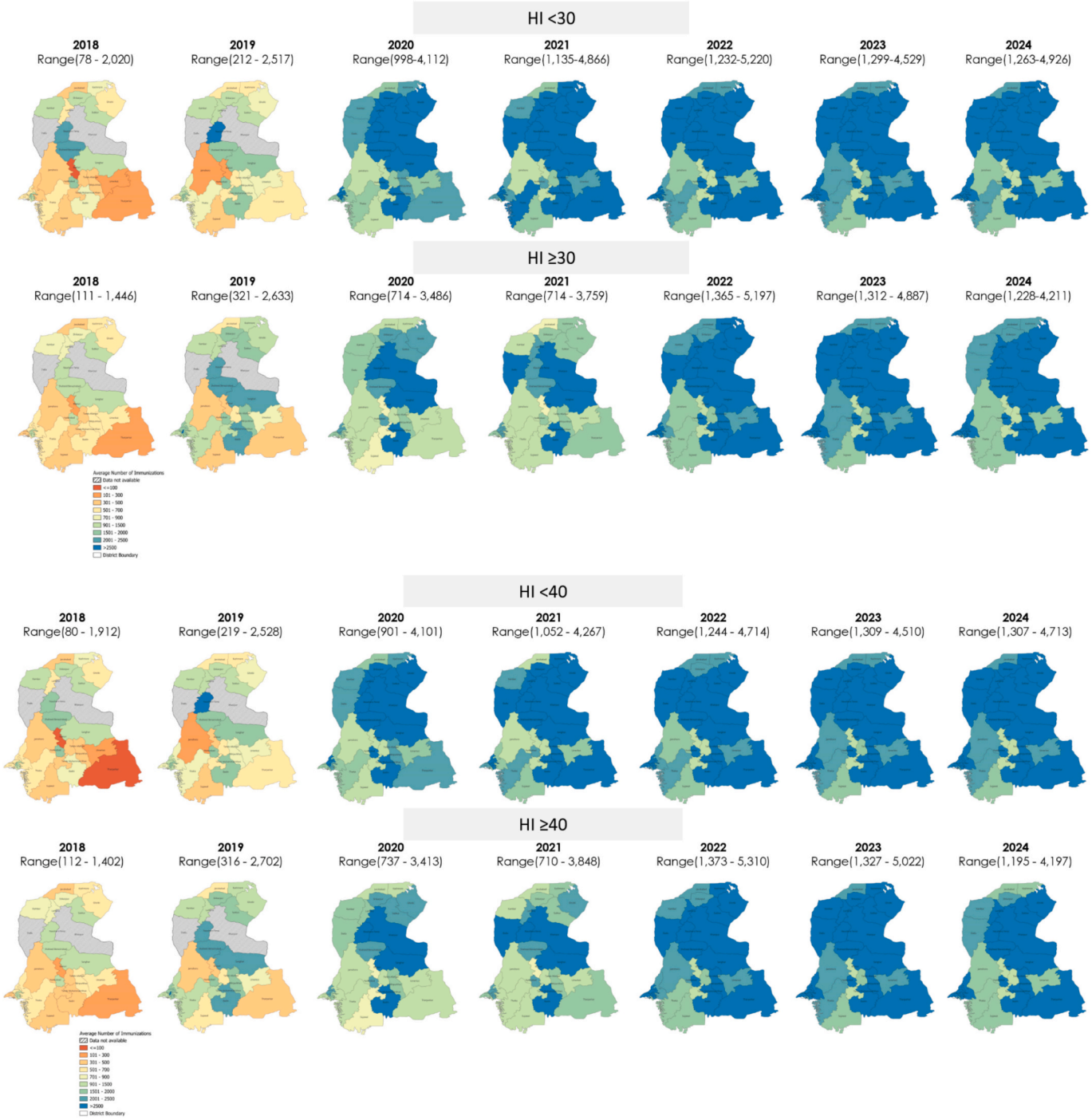

Fig. 3. District-wise GIS maps showing the average number of immunizations administered during the low and high heat index across Sindh Province, Pakistan, by years, January 1, 2018-July 31, 2024.

effect. This variability likely reflects differences in regional vulnerability and adaptive capacity to extreme heat. Larkana and Sukkur, being predominantly rural areas with limited healthcare infrastructure and resources [44], are more susceptible to disruptions from extreme weather events. In contrast, Karachi, as a major urban center, benefits from more robust infrastructure, greater access to healthcare facilities, and potentially more effective heat mitigation strategies, which may buffer the adverse effects of heat waves on immunization services. These findings highlight the importance of tailoring public health interventions to regional contexts and investing in infrastructure and resources in vulnerable areas to enhance resilience against climate-related disruptions. Likewise, in certain years immunizations increased during the high heat index periods, notably in 2019 with marginal increases also observed in 2022 and 2023.

We found some counter intuitive results on the impact of external shocks on immunization rates. While many global reports document the negative impacts of floods and pandemics on healthcare services [45], we observed that immunizations in Sindh province rebounded and recovered with an overall increase in immunization doses in 2022 and 2023 during both the floods and the later phases of the COVID-19 pandemic. Several factors contributed to maintaining immunizations during these external shocks. Although floods typically disrupt routine

Table 1
Impact of heat wave on total immunizations administered through fixed sites across Sindh Province, Pakistan January 1, 2018 - July 31, 2024.

Variables	Model-1				Model-2				Model-3			
	IRR	P-value	95 % CI		IRR	*P*-value	95 % CI		IRR	P-value	95 % CI	
Heat index ≥ 33 °C												
No	Ref											
Yes	0.942	<0.001	0.930	0.954								
Heat index ≥ 40 °C												
No					Ref							
Yes					0.939	<0.001	0.928	0.951				
Heat index categories												
Tolerable <33 °C									Ref			
Caution/extreme caution (33–39 °C)									0.990	0.357	0.970	1.011
Danger (40–53 °C)									0.975	0.002	0.959	0.991
Extreme Danger (≥54 °C)									0.918	<0.001	0.904	0.931
Floods												
No	Ref				Ref				Ref			
Yes	1.062	<0.001	1.035	1.090	1.055	<0.001	1.029	1.083	1.040	0.003	1.013	1.068
Covid pandemic												
No	Ref				Ref				Ref			
Yes	1.064	<0.001	1.051	1.077	1.062	<0.001	1.050	1.075	1.065	<0.001	1.052	1.078
Vaccinator strike												
No	Ref				Ref				Ref			
Yes	0.527	<0.001	0.510	0.544	0.526	<0.001	0.510	0.543	0.526	<0.001	0.509	0.543
AIC	**935,871**				**935,846**				**932,090**			

Table 2
Impact of heat wave on total immunizations administered through ROA across Sindh Province, Pakistan.

Variables	Model-1				Model-2				Model-3			
	IRR	P-value	95 % CI		IRR	P-value	95 % CI		IRR	P-value	95 % CI	
Heat index ≥ 33 °C												
No	Ref											
Yes	0.864	<0.001	0.850	0.878								
Heat index ≥ 40 °C												
No					Ref							
Yes					0.849	<0.001	0.837	0.861				
Heat index categories												
Tolerable <33 °C									Ref			
Caution/extreme caution (33–39 °C)									0.996	0.747	0.972	1.021
Danger (40–53 °C)									0.936	<0.001	0.917	0.954
Extreme Danger (≥54 °C)									0.800	<0.001	0.786	0.815
Floods												
No	Ref				Ref				Ref			
Yes	1.650	<0.001	1.606	1.695	1.627	<0.001	1.584	1.671	1.563	<0.001	1.520	1.607
Covid pandemic												
No	Ref				Ref				Ref			
Yes	1.323	<0.001	1.303	1.343	1.317	<0.001	1.297	1.337	1.318	<0.001	1.298	1.339
Vaccinator strike												
No	Ref				Ref				Ref			
Yes	0.514	<0.001	0.494	0.535	0.512	<0.001	0.492	0.533	0.510	<0.001	0.490	0.531
AIC	**815,014**				**814,847**				**810,709**			

vaccinations by hindering travel to healthcare facilities and limiting the ability of vaccination teams to reach target populations [46], the severe floods from mid-June to October 2022 in Pakistan displaced large populations into communal shelters, facilitating intensified immunization efforts to prevent VPD outbreaks [47]. Remarkably, immunizations through ROAs rose by 65.0 % during the floods compared to a modest 6.2 % increase through fixed sites. This significant rise in ROA immunizations was likely due to targeted outreach efforts in relief camps and communal shelters, where displaced populations were concentrated, thus facilitating easier access to vaccination services. Over 2500 vaccinators were deployed to provide routine immunization services to children who had relocated to or sought shelter in relief camps across 23 flood-affected districts in Sindh [48]. Similarly, although the COVID-19 pandemic caused substantial declines in routine immunization services globally, particularly in LMICs [49,50], in Sindh province, immunizations rebounded after an initial reduction during lockdowns. Extended outreach activities were carried out to cover defaulters and support polio campaigns [51] facilitated by data-driven decision making. Furthermore, the establishment of 56 new immunization centers and the recruitment of 321 vaccinators in 2023 further bolstered immunization coverage. These proactive measures contributed to mitigating the adverse effects typically seen during crises, highlighting the critical role of adaptive strategies in maintaining essential health services during emergencies.

Our study has a few limitations. First, as an observational ecological study, it cannot establish causality between heat waves and declines in immunization rates. Although the analysis controls for external factors such as floods, vaccinator strikes, and the COVID-19 pandemic, unmeasured confounders, such as local political instability, healthcare workforce shortages, or differences in healthcare infrastructure, may still affect the observed associations. Moreover, the study does not incorporate individual-level variables like socio-economic status or household-specific barriers to healthcare access, which could influence immunization rates during heat waves. For instance, poorer households may encounter greater obstacles in accessing health services during heat waves due to factors like lack of transportation or limited awareness of

Table 3
Impact of heat wave on total immunizations administered through EOA across Sindh Province, Pakistan.

Variables	Model-1				Model-2				Model-3			
	IRR	P-value	95 % CI		IRR	P-value	95 % CI		IRR	P-value	95 % CI	
Heat index ≥ 33 °C												
No	Ref											
Yes	0.788	<0.001	0.762	0.815								
Heat index ≥ 40 °C												
No					Ref							
Yes					0.773	<0.001	0.748	0.799				
Heat index categories												
Tolerable <33 °C									Ref			
Caution/extreme caution (33–39 °C)									1.017	0.638	0.949	1.090
Danger (40–53 °C)									0.946	0.012	0.905	0.988
Extreme Danger (≥54 °C)									0.713	<0.001	0.687	0.740
Covid pandemic												
No	Ref				Ref				Ref			
Yes	1.438	<0.001	1.389	1.489	1.421	<0.001	1.373	1.471	1.427	<0.001	1.379	1.478
Vaccinator strike												
No	Ref				Ref				Ref			
Yes	0.697	<0.001	0.636	0.765	0.694	<0.001	0.633	0.760	0.698	<0.001	0.638	0.765
AIC	**138,878**				**138,828**				**138,214**			

vaccination campaigns, nuances not captured in the district-level aggregate data. Further research is needed to investigate the individual-level risk factors of the impact of heat waves on immunization coverage to explain some of our findings in more detail. Additionally, the study focuses solely on Sindh Province, and while the findings provide valuable insights, they may not be fully generalizable to regions with different climate patterns, healthcare systems, or socio-economic conditions. Further research is required to assess whether these findings apply to other LMICs facing similar climate-related challenges.

Effectively countering the adverse impacts of climate change on immunization services requires a two-pronged approach aimed at mitigating adverse impacts as well as making health systems more resilient, enabling them to adapt to future challenges. Mitigation strategies can include leveraging technologies such as robust EIRs to track children's immunization status, develop data-driven micro plans, and implement targeted outreach campaigns to identify and vaccinate under-immunized populations, particularly in heat wave-prone areas. Existing technologies such as location-based SMS can be used to provide updates on adjusted clinic hours or locations during periods of extreme heat. Cold chain management can be strengthened through establishing decentralized cold chain facilities with reliable backup power to maintain vaccine potency during heat wave-induced outages and using continuous monitoring systems with alerts for temperature excursions. Additionally, the increased risk of cold chain disruptions due to refrigeration failures and transport interruptions during heat waves also warrants the robust use of vaccine vial monitors (VVMs) in settings vulnerable to extreme heat to ensure vaccine potency is not compromised. Furthermore, maintaining immunization services also requires a concerted effort to train vaccinators on strategies for maintaining cold chain integrity during extreme heat, identifying and managing heat-related illnesses (heat stroke, heat exhaustion) in children and caregivers and effective communication strategies to address vaccine hesitancy in the context of climate change. Likewise, community engagement needs to be strengthened to make caregivers aware of the importance of immunization even during extreme heat and providing them with tools and support for preventative care of heat-related illnesses and logistical assistance to reach immunization clinics during high temperatures.

Additionally, several adaptations can be made to cold chain management, data analysis and logistics to make immunization services more resilient to the impacts of climate change and extreme heat events. Currently, Pakistan's EPI is mitigating heatwave effects on the supply side by upgrading its cold chain infrastructure to ensure vaccine integrity. Key improvements include the installation of solar-powered refrigerators, the deployment of remote temperature monitoring devices (RTMDs), and the use of real-time dashboards to address electricity shortages and maintain optimal storage conditions. These enhancements can help preserve vaccine potency under rising temperatures, ensuring effective immunization throughout all tiers of the healthcare system [52]. Additionally, countries should adapt data monitoring to account for heat wave-specific indicators to track the impact of extreme heat on immunization coverage and identify areas needing improvement. Data analysis should also incorporate immunization rates, heat wave occurrences, and community demographics to identify trends and inform targeted approaches. We found that fixed sites appear to be less vulnerable to extreme heat, therefore, their maintenance is important ensuring they are well-ventilated and equipped with a reliable cooling system that ensures proper storage to maintain the viability of vaccines [8]. Outreach activities are essential for reaching vulnerable and isolated populations, who are more likely to miss vaccinations [53]. Since these activities were the most affected by extreme heat, further action is needed to strengthen their capacity to operate under such conditions including rescheduling outreach to cooler parts of the day, improving transportation options for health workers and vaccines and providing logistical support as well as incentives for vaccinators to maintain immunizations via outreach.

In the long term it is essential to integrate climate change considerations into long-term healthcare planning and vice versa to protect lives, especially of the most marginalized. This was also underscored at the COP29 special report on climate and health and Pan American Health Organization (PAHO's) Policy to strengthen Equity-Oriented Health Sector Action on Climate Change and Health.

This study highlights the urgent need for further investigation into the effects of extreme heat events, such as heat waves, on immunization activities in regions susceptible to climate change. Future research should prioritize the development and implementation of strategies to enhance the resilience of immunization systems against extreme weather conditions. Expanding research to additional geographic regions with similar climates and public health challenges is essential for understanding the broader implications of heat waves on vaccination efforts. Comparative analyses across LMICs could identify common obstacles and solutions that may be applicable globally. Longitudinal studies are also necessary to evaluate the sustainability and adaptability of immunization programs in response to heat waves, with an emphasis on tracking the impact of climate interventions over time to identify the most effective practices for maintaining high vaccination coverage under environmental stressors.

5. Conclusion

Our study shows a 5.8 % and 13.6 % decline in immunizations respectively at fixed sites and outreach during heat waves compared to periods of routine temperature in Sindh province over the last five years. The decline was particularly pronounced for outreach immunization activities. Geographic and temporal heterogeneities in the impact indicate the need for further investigation. Our findings underscore the vulnerability of health systems to climatic variations and call for urgent policy action corroborating the efforts of WHO, UNICEF and PAHO at the recent COP-29 meetings. Policymakers should adopt a two-pronged approach of mitigating the impacts of climate change and prioritizing adaptation investments in climate-resilient health infrastructure, health worker support, adaptive systems, and outreach strategies tailored to extreme weather conditions. Strengthening the vaccine cold chain, optimizing outreach schedules, and ensuring reliable transportation, equipment and support for health workers can prove critical in mitigating the impact of heat waves on immunization services. Future research should examine individual-level socio-economic factors that influence immunization access during extreme weather events to develop targeted interventions with enhanced resilience in the face of escalating climate challenges.

CRediT authorship contribution statement

Danya Arif Siddiqi: Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Sundus Iftikhar:** Writing – original draft, Visualization, Methodology, Formal analysis. **Christian Moretti Anfossi:** Writing – review & editing, Writing – original draft. **Muhammad Siddique:** Visualization, Methodology. **Mubarak Taighoon Shah:** Resources, Project administration, Funding acquisition. **Vijay Kumar Dharma:** Resources, Project administration. **Mariam Mehmood:** Resources, Project administration. **Hamidreza Setayesh:** Writing – review & editing, Visualization. **Irshad Ali Sodhar:** Writing – review & editing, Visualization. **Farrukh Raza Malik:** Writing – review & editing, Visualization. **Subhash Chandir:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization.

Informed consent statement

"Not applicable."

Institutional review board statement

This analysis was deemed to be exempt by the Institutional Review Board of Interactive Research and Development under 45 CFR 46.101(b) (study number: IRD_IRB_2020_04_018). The IRB was registered with the U.S. Department of Health and Human Services Office for Human Research Protections with registration number IRB 40400005148.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.vaccine.2025.127424.

Data availability

Data may be obtained from a third party and are not publicly available. The data used for this analysis is from the provincial electronic immunization registry can be requested from Government of Sindh's Expanded Programme on Immunization (EPI) Program.

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