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First-line childhood vaccination coverage in Sakarya Province, Türkiye: a service-delivery-unit and district-level multilevel and spatial analysis

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Abstract

Background

Global childhood immunization rates have plateaued, and the WHO European Region has experienced its largest measles outbreak in over 25 years. Although elimination targets are set for each community, monitoring typically occurs at the national or district level, with little attention to service-delivery specifics. Coverage data alone does not indicate whether doses are administered on time. We investigated coverage, timeliness, and off-schedule doses specifically at the service-delivery-unit level.

Methods

This record-based study covered all primary care in Sakarya Province, Türkiye: 64,678 unit-month observations from all 349 family medicine units across 99 family health centers and 16 districts over 24 months (October 2023–September 2025) and nine vaccine-dose units. Outcomes were total coverage, timely coverage, and off-schedule administration. Generalized linear mixed models used nested random effects for district, center, and unit, plus crossed intercepts for vaccine-dose unit; binomial or beta-binomial families were selected based on overdispersion diagnostics. Variance was partitioned using intraclass correlation coefficients (ICC), and spatial clustering was assessed with global and local Moran's I (LISA).

Results

Pooled coverage was 90.2–93.8%, but only 71.3–82.6% of unit-months reached ≥ 95%, with the second measles-containing dose lowest (90.2%; 71.3%). Off-schedule administration was 0.4–1.2%. Per standard deviation, mean household size was associated with lower total coverage (OR 0.87, 95% CI 0.78–0.96) and lower timely coverage (OR 0.88, 0.79–0.97), significant in eight of nine units. Education was associated with lower timely coverage (OR 0.89, 0.82–0.96) and more off-schedule administration (OR 1.20, 1.02–1.40), but with total coverage in only two units. Presence of a specialist physician was associated with higher total coverage (OR 1.25, 1.04–1.50) and higher timely coverage (OR 1.23, 1.03–1.47). Physician turnover and physician-absent months were not significant. Total ICC was 0.086 (unit 5.9%, center 1.8%, district ≈ 0%) and 0.201 for off-schedule administration. Global clustering was significant for one unit.

Conclusions

Coverage was generally high and geographically equitable. However, many unit-months still fell below the elimination threshold, especially for the second measles dose. Variance was mostly observed at the smallest service units rather than at the district level, suggesting that prioritization should be delegated to the practice level. Education contributed to delayed rather than missed vaccinations, and increasing specialist staffing is a changeable supply-side factor. Timeliness should be monitored routinely alongside coverage.

Background

Childhood immunization is among the most cost-effective of all public health interventions. Since the launch of the Expanded Programme on Immunization in 1974, an estimated 154 million child deaths have been averted worldwide (1). Nevertheless, gains have stalled over the past fifteen years, and the COVID-19 pandemic turned this stagnation into

a clear decline. According to the most recent WHO/UNICEF national immunization coverage estimates (WUENIC), published in July 2026, 90% of infants received the first dose of the diphtheria-tetanus-pertussis vaccine in 2025 and 85% completed the three-dose series. Although both indicators rose by one percentage point relative to the previous year, global coverage remains one point below the 2019 level and has fluctuated within a narrow band since 2009. In the same year, 13.5 million children received no vaccine dose at all, and a further 6.2 million were only partially protected (2, 3). The Global Burden of Disease 2023 analysis confirms this picture and projects that, if current trends persist, the 90% target of the Immunization Agenda 2030 (IA2030) will be reached only for DTP3 and only under an optimistic scenario (1, 4).

The problem underlying this stagnation, increasingly apparent in recent years, is not only that children are never reached but also that those who are reached fail to complete the schedule. In 2025, 7.3 million infants received their first DTP dose but dropped out of the program before receiving the first measles dose. This discontinuity directly lowered measles coverage, which remained at 84% for the first dose and only 77% for the second. Both values fall well below the 95% threshold required to prevent outbreaks, and in 2025 fifty-seven countries reported large or disruptive measles outbreaks (3). The WHO European Region provided the most visible example of this fragility: the 127,350 measles cases reported in 2024 were the highest since 1997, and more than 40% of cases occurred in children under age five (5). Although intensified response brought the case count down to 33,998 in 2025, the number of countries reporting endemic transmission rose from 12 to 19, and in January 2026 six countries lost their elimination status(6). Elimination frameworks therefore require that ≥ 95% coverage with two doses of measles-containing vaccine be sustained not only nationally but in every sub-region(7, 8).

The critical point here is the scale at which the target is defined. Immunization performance continues to be reported largely through national and regional averages; yet these averages can conceal substantial sub-national heterogeneity. UNICEF's assessment of the 2026 estimates likewise stresses that the true measure of progress is not regional averages but whether every family can access and trust services(2). Indeed, an analysis covering 1,366 administrative areas in 43 countries identified marked regional gaps beneath national rates(9); in one Nigerian state, full immunization coverage of 94.5% in urban areas fell to 55.5% in rural areas(10). A spatio-temporal estimation covering 38 African countries showed that some countries meeting national targets fell short of the target across all of their sub-regions(11). More importantly, low-coverage clusters are not confined to poorly performing countries; spatially clustered susceptible subpopulations have been documented even in countries with high national coverage(12). However, the resolution of this literature usually remains at the district or regional level, and the unit at which services are actually delivered and accountability is defined is rarely used as the unit of analysis. Routine health-facility records have also been shown to be increasingly suitable for such fine-resolution monitoring(13).

Refining resolution is not sufficient on its own; the content of what is measured must also be questioned. Coverage is traditionally defined as completing a vaccine series by a given age, a definition that obscures whether doses were administered at the prescribed times. In a prospective study in Uganda, coverage for individual vaccines exceeded 90%, whereas only 18% of children received all vaccines within the recommended intervals (14). In Jerusalem, while coverage at two years of age ranged from 86% to 95%, age-appropriate vaccination rates fell to 20–58%(15). In the United States, using nationally representative data, the proportion of children who had received all doses on time by age 19 months remained at 41.2% (16). Because delayed vaccination prolongs the window during which a child remains susceptible and thereby increases outbreak risk, monitoring timeliness as a core program-quality indicator has been advocated with growing force(17, 18). Electronic immunization registries allow performance metrics to be redefined beyond aggregate coverage(19); a registry-based analysis of 6.2 million children in Pakistan revealed that, while coverage appeared high, timely administration remained at 31–37%(20). By contrast, studies that model off-schedule administration - that is, administering a dose outside the prescribed age window - as an independent dimension of

performance at the service-delivery-unit level are quite limited. For this reason, in the present study, performance is examined using three separate measures: total coverage, timely coverage, and off-schedule administration.

As much as how performance is measured, what determines it is also unclear. The literature on determinants has focused predominantly on the demand side. Individual- and household-level factors, such as maternal education, household income, household size, birth order, and vaccine hesitancy have been extensively documented(21); however, the direction of these associations varies by context, and reversal of the socioeconomic gradient has been reported particularly in high-income countries(22). The supply side - that is, the characteristics of the unit delivering the service - has been far less quantified. In an analysis of 1,346 health sub-centers in India, facility infrastructure quality was positively associated with both full immunization and timely vaccination(23); in Nigeria, the contribution of supply-side access indicators to explaining regional differences was examined(24). Provider characteristics have also been shown to directly affect the timing of a child's vaccination(25). Designing immunization services and primary care to be mutually reinforcing lies at the centre of debates on universal health coverage(26).

When these two axes are brought together, the unanswered question is: at which level do coverage differences arise, and hence at which level should intervention be targeted? The established targeted-planning tradition of immunization programmes - as in the WHO and UNICEF 'Reaching Every District' approach - rests on prioritising poorly performing administrative areas(27). Yet the correct rung for such prioritisation is an empirical question, and its answer can be given through variance decomposition: whether variability is concentrated between districts or between units within the same district can be measured directly with the intraclass correlation and variance components(28, 29). That these measures are not routinely reported in the immunization literature leaves targeting decisions without an empirical basis.

Türkiye offers a favorable setting for filling this gap. Through the Family Medicine Programme, implemented gradually between 2005 and 2010, primary care was restructured on a registered-population model. Each family medicine unit (FMU) is the smallest accountable service-delivery unit, responsible for a defined population registered to it; FMUs are nested within family health centres (FHCs), and FHCs within districts(30, 31). This structure ensures that almost all childhood vaccines are delivered through a defined unit and recorded electronically, enabling performance analysis of every unit across the province. Concerns about vaccine hesitancy have also grown over the same period: hesitancy was detected among 32% of parents in south-eastern Anatolia(32), and the level of hesitancy was shown to vary significantly between regions of differing socioeconomic profile(33). The combination of a strong and standardised service infrastructure with a heterogeneous demand environment makes it both possible and necessary to disentangle at which level and through which mechanisms the remaining differences in coverage arise. Nevertheless, no study in Türkiye has modelled immunization performance at the service-delivery-unit level across multiple antigens and multiple months, together with the dimensions of timeliness and off-schedule administration.

Aim

The aim of this study is to evaluate first-line childhood vaccination performance in Sakarya Province at the service-delivery-unit level, in a multidimensional manner, using a registry-based dataset covering every unit across the province. Over the 24-month period from October 2023 to September 2025, nine vaccine-dose units were examined using 64,678 observations at the FMU x month x vaccine-dose level, belonging to 16 districts, 99 FHCs and 349 FMUs. The specific objectives are as follows:

- To define total coverage, timely coverage and off-schedule administration as three separate dimensions of performance and to describe them at the vaccine-dose-unit level; in particular, to quantify the proportion of unit-months reaching the ≥ 95% threshold.

- To estimate the associations of service-delivery-level characteristics (physician turnover, physician-absent month proportion, registered-population structure, unit density, presence of a specialist physician) and district-level contextual characteristics (mean years of schooling, household size, child dependency ratio) with these three dimensions, using generalised linear mixed models with nested random effects of district/FHC/FMU.
- To determine empirically the rung at which monitoring and intervention should be targeted, by decomposing at which level (district, FHC, FMU) variability is concentrated through the intraclass correlation and variance components.
- To test geographical clustering at the FHC level with spatial autocorrelation analyses, to identify priority hot and cold spots requiring intervention using the local Moran (LISA) statistic, and to assess the sensitivity of findings to the neighbourhood definition.
- To assess the consistency of determinants across the nine vaccine-dose units by comparing pooled and unit-specific models.

To our knowledge, this is the first study in Türkiye to examine first-line vaccination performance at the service-delivery-unit level, across multiple antigens and over a consecutive 24-month window, using multilevel and spatial methods that additionally incorporate the dimensions of timeliness and off-schedule administration alongside coverage. By making visible the unit-level differences concealed by national averages, the findings are expected to contribute to the design of targeted micro-interventions, to risk-profiling practices in primary health-care management, and to immunization monitoring approaches in health systems with a similar registered-population model. The unit- and centre-level outputs obtained are intended to be of a quality that can directly inform microplanning decisions at the provincial scale.

Methods

Study design, setting and time frame

This is a registry-based, retrospective cross-sectional, ecological study examining first-line vaccination performance in Sakarya Province at the service-delivery-unit (family medicine unit, FMU) level. The analysis combines a multilevel (hierarchical) component at the FMU level with a contextual (ecological) component at the district level. The study setting comprises the 16 districts of Sakarya, and the observation window covers the 24 consecutive months from October 2023 to September 2025. The unit of analysis was defined as FMU x month x vaccine-dose; each observation represented the performance of a given FMU in a given calendar month for a given vaccine-dose.

Data sources and linkage

The vaccination data comprised four datasets. The first dataset contained the monthly vaccination performance of FMUs (at the month-vaccine-dose level), and the second contained the service-delivery characteristics of FMUs (physician occupancy rates and registered-population information). These two datasets were obtained from the electronic records database of the Sakarya Provincial Health Directorate (PHD). The third dataset contained the geographical coordinates of the FHCs across Sakarya; these were obtained manually by cross-verification using Google Maps and Yandex Maps, and their consistency with the FHC addresses on the PHD website was verified. The fourth dataset consisted of socioeconomic and demographic indicators for the districts of Sakarya (n = 16) - mean years of schooling, mean household size, Socioeconomic Development Ranking (SEGE) score, and child and old-age dependency ratios - and was obtained from the open-data system of the Turkish Statistical Institute (TurkStat).

Study scope and sample

Across Türkiye, first-line vaccination services are provided by FHCs, with services within FHCs delivered by the FMU, which consists of one physician and one auxiliary health worker. In this system, each FMU serves a defined registered population. Across Sakarya, there were 116 active FHCs and 385 active FMUs during the study period. The total population registered with these FMUs was 1,093,763 as of September 2025. The median population registered with each FMU was 3,110 (Q1-Q3: 3,009.75-3,425.50). According to 2025 TurkStat statistics, the number of children aged 0–4 years in Sakarya was 61,971 (5.51%).

FHCs and FMUs with special circumstances were excluded from the analysis: FHCs in prisons, FHCs established for training purposes and affiliated with universities, newly opened units with zero registered population, and FMUs with a registered-population z-score below − 3. In addition, units with missing physician information were excluded only from analyses relating to physician variability. After applying these criteria, the analytic sample comprised 16 districts, 99 FHCs, and 349 FMUs.

Nine vaccine-dose units on the childhood immunization schedule were included in the evaluation: BCG dose 1; hepatitis A (HepA) doses 1 and 2; measles-mumps-rubella (MMR) doses 1 and 2; pneumococcal conjugate vaccine (PCV) doses 1 and 2 and booster; and varicella (VAR) dose 1. Among the other antigens in the source database, hepatitis B, polio, tetanus, diphtheria, pertussis, and Hib were excluded to preserve analytic integrity, as they are included in various combination vaccines. The selected vaccines were those not part of combination vaccines, contained all vaccine doses over the study period, and were not interrupted by changes to the immunization schedule.

Dependent variables

The data forming the study's principal dependent variables were: the number of children for whom the relevant dose was due (scheduled) in the relevant month (due); the number of doses administered on time (timely administered); the sum of timely and off-schedule administrations (total administered); and the number of doses administered off schedule (off-schedule administered). Whether a dose was counted as timely or off-schedule was determined by the Ministry's information system. In this study, these counts were used to derive three coverage measures. These variables were computed for each month and vaccine-dose within the relevant FMU.

- • Total coverage (TC) = total administered / due
- • Timely coverage (TMC) = timely administered / due
- • Off-schedule ratio (OSR) = off-schedule administered / total administered

Ratios were treated as undefined in FMU-month observations with a zero denominator.

Independent variables

Service-delivery-level (FMU/FHC) variables were defined as: physician turnover, physician-absent month proportion, variability in FMU population (coefficient of variation), median FMU population, number of FMUs per FHC, and presence of a specialist physician at the FHC. District-level variables comprised mean years of schooling, mean household size, and child dependency ratio. Season was included in the models to account for possible seasonal patterns (reference category: summer).

Among the candidate variables, the district SEGE score and the old-age dependency ratio were excluded from the final model due to marked multicollinearity. The SEGE score was very highly correlated with mean years of schooling (r = 0.95), and the old-age dependency ratio was strongly correlated with schooling and SEGE (r = -0.75 and r = -0.79, respectively); including both variables simultaneously raised the variance inflation factors to unacceptable levels.

Statistical analysis

Descriptive analysis

For each vaccine-dose unit, coverage measures were calculated as dose-weighted pooled ratios (across total shares across observations). The coverage distribution was described by dividing it into bands (≤ 50%, 50–79%, 80–94%, ≥ 95%).

Mixed-effects regression: model set-up

The association between service-delivery- and district-level characteristics and coverage was examined using generalized linear mixed models (GLMMs; mixed-effects logistic regression). The fixed effects comprised: physician turnover, proportion of months with absent physicians, variability in FMU population (coefficient of variation), number of FMUs per FHC, median FMU population, presence of a specialist physician at the FHC (binary), mean years of schooling, mean household size, child dependency ratio, and season (four categories; reference: summer). Continuous variables were z-standardized before entering the model (mean 0, standard deviation 1); thus, for these variables, odds ratios are interpreted as per one-standard-deviation increase.

The random-effects structure was defined, to reflect the hierarchy of the data, as nested (three-level) random intercepts with FHC within district and FMU within FHC. In the pooled model in which all units were modelled together, an additional crossed random intercept for vaccine-dose unit (1 | unit) was added to account for baseline differences among the nine vaccine-dose units. The monthly time dimension was incorporated into the model as a fixed effect via the season variable.

Choice of distributional family

The distributional family was determined diagnostically for each model. A binomial GLMM with a logit link was fitted first; overdispersion was then assessed using simulation-based residual diagnostics. In models where overdispersion was detected, a beta-binomial family, which directly models observation-level extra variability, was tried. When overdispersion could not be resolved even under the beta-binomial, the binomial family was taken as the reference. As a result, the reference distributional family reported varies across models and is stated for each model in Additional file 1: Table S5. For most off-schedule models, the beta-binomial family was taken as the reference owing to the strongly zero-inflated distribution of the response.

Estimation, effect sizes and model reporting

Models were estimated with the glmmTMB package using maximum likelihood based on the Laplace approximation. For fixed effects, odds ratios were calculated as the exponentiated coefficients (OR = exp(beta)) and 95% confidence intervals by the Wald method (exp[beta +/- 1.96 x SE]). Both the crude (univariable) and adjusted (all variables in the model) odds ratios of each determinant were additionally compared; adjusted (multivariable) estimates are reported in the text.

Between-level clustering was summarised with the intraclass correlation coefficient (ICC); the ICC was calculated on the latent scale as the ratio of the variance of the relevant random-effect level to the total variance (the sum of the random-effect variances and the logistic-distribution-specific residual variance pi^2/3 ~ = 3.29), and was reported both by level and in total. The variance explained by the model was reported, following the method of Nakagawa and Schielzeth, as the marginal R^2 (fixed effects only) and the conditional R^2 (fixed + random effects); the theoretical (delta) variance approximation was used for the binomial family. Because the marginal R^2 could not be reliably defined for

beta-binomial fits and for the strongly zero-inflated off-schedule distributions, it was not reported for these models, and explanatory power was assessed via the ICC.

The overall significance of the model was tested with a likelihood-ratio test comparing the full model to the null model containing only random effects (LRT; chi-square, degrees of freedom = number of fixed-effect parameters). The unique contribution of each determinant was assessed with a likelihood-ratio test comparing the model obtained when that variable was removed to the full model (drop-one LRT). Fixed effects, variance components, ICC, Nakagawa R2 values, and fit measures (AIC, BIC, logLik, deviance) are presented for the pooled models in Table 2 of the main text and for all models in Additional file 1: Table S2.

Table 2
Pooled GLMM results for coverage determinants: fixed effects (OR), variance components and fit

Determinant	TC OR (95% CI)	TMC OR (95% CI)	OSR OR (95% CI)
Household size	0.87 (0.78–0.96)**	0.88 (0.79–0.97)*	0.97 (0.80–1.19)
Mean years of schooling	0.90 (0.82–0.98)*	0.89 (0.82–0.96)**	1.20 (1.02–1.40)*
Child dependency ratio	0.99 (0.89–1.10)	0.97 (0.87–1.07)	1.23 (1.00–1.51)*
Specialist physician (present) □	1.25 (1.04–1.50)*	1.23 (1.03–1.47)*	1.07 (0.76–1.50)
Physician turnover	0.97 (0.91–1.03)	0.97 (0.91–1.03)	1.04 (0.92–1.17)
Physician-absent month proportion	1.00 (0.94–1.06)	0.99 (0.94–1.05)	0.99 (0.89–1.11)
Median FMU population	0.96 (0.90–1.03)	0.98 (0.91–1.05)	0.94 (0.83–1.08)
Number of FMUs per FHC	0.93 (0.84–1.03)	0.94 (0.85–1.03)	0.96 (0.80–1.15)
Population variability (CV)	0.97 (0.93–1.03)	0.98 (0.93–1.02)	1.05 (0.94–1.16)
Season: Winter □	1.12 (1.07–1.17)***	1.07 (1.02–1.11)**	1.67 (1.42–1.96)***
Season: Spring □	0.97 (0.93–1.01)	0.95 (0.91–0.99)*	1.48 (1.26–1.75)***
Season: Autumn □	1.05 (1.00–1.10)*	1.02 (0.98–1.07)	1.40 (1.19–1.65)***
Random effects (variance) and model fit			
Variance: FMU (district/FHC/FMU)	0.214	0.193	0.536
Variance: FHC (district/FHC)	0.064	0.059	0.171
Variance: District	0.000	0.000	0.000
Variance: Unit (vaccine-dose)	0.032	0.037	0.123
ICC — total	0.086	0.081	0.201
Marginal R^2 (Nakagawa)	0.031	0.031	0.048
Conditional R^2 (Nakagawa)	0.261	0.249	0.465
AIC	73,527	77,045	12,056
LRT (full vs null), $\chi^2(12)$	65.6***	53.5***	54.5***
n (FMU-month observations)	64,678	64,678	63,572 □

*Fixed effects are ORs per one-standard-deviation increase (continuous variables z-standardised; specialist physician binary). Asterisks: * p < 0.05; ** p < 0.01; *** p < 0.001. □ Reference: no specialist physician. □ Reference: summer. Variances are the variance components of the random intercepts; the ICC is the between-level variance share; marginal R^2 = variance explained by fixed effects, conditional R^2 = by fixed + random effects (Nakagawa). LRT = likelihood-ratio test of the full model against the null model. The reference distributional family is binomial for all three responses. OR > 1 increases the relevant measure; for off-schedule administration a high value is unfavourable. □ Observations with a zero denominator were excluded.*

Modelling was carried out at two complementary levels. Pooled models (the nine units together, with an additional random intercept for vaccine-dose unit) were built to estimate average/overall associations with greater statistical power; unit-specific models (a separate GLMM for each vaccine-dose) were built to estimate unit-specific odds ratios and to assess the consistency of associations across units.

Spatial analysis

Geographical clustering was examined at the FHC level using the 99 FHCs for which geolocation was available. Neighbourhood was defined as a row-standardised weight matrix based on the k = 3 nearest-neighbour criterion; global spatial autocorrelation was tested with the global Moran's I based on Monte Carlo permutation (999 iterations). The sensitivity of results to the neighbourhood definition was assessed by repeating the same analysis with the k = 4 and k = 5 nearest-neighbour criteria. Local clusters (hot/cold spots) were identified with the local Moran statistic (LISA, alpha = 0.05). In addition, the distance of each FHC to its nearest neighbour (isolation) was calculated, and its association with coverage was assessed with the Pearson correlation.

Model diagnostics

The fitted GLMMs were checked for multicollinearity (variance inflation factor, VIF), simulation-based residual analysis (DHARMa; distributional fit), overdispersion, and residual spatial autocorrelation (Moran's I on residuals reduced to the FHC level). VIF assessment was used to determine the set of explanatory variables, and overdispersion assessment to choose the distributional family.

Software

All analyses were conducted in the R statistical environment (version 4.4.3); the glmmTMB package was used for mixed models, spdep for spatial analyses, and DHARMa and performance for model diagnostics. Statistical significance was evaluated at the two-sided alpha = 0.05 level.

Use of large language models and artificial intelligence tools

Artificial intelligence (AI) tools were used to generate auxiliary R code for preparing the analytic data. Specifically, AI assistance was used to prepare and merge the 450 separate Excel (.xls) packages obtained from the Ministry of Health into a single dataset, and to prepare the 24-month x 349-FMU data obtained from the Provincial Health Directorate for analysis.

AI tools were also used in developing the analysis application (an R/Shiny tool); the analysis code has been made publicly available at the repository link provided under 'Availability of data and materials'.

The Consensus AI tool (https://consensus.app) was used to support the literature search.

Claude.ai and Grammarly were used to translate the manuscript into English and to proofread it.

The authors reviewed, verified and edited all AI-assisted outputs and take full responsibility for the integrity and content of the manuscript. AI tools were not used to generate scientific interpretations or conclusions and do not meet authorship criteria; accordingly, no AI tool is listed as an author.

Ethics

Approval for the study was obtained from the Scientific Research Ethics Committee of Health Sciences, Faculty of Medicine, Sakarya University (application date 31 July 2025, application no. 479; decision date 20 September 2025, no. E-43012747-050.04-513197-479). The study was retrospective and registry-based, using aggregated data with no personal identifiers.

Results

Sample and descriptive findings

The analytic sample covered 99 family health centers (FHCs) and 349 family medicine units (FMUs) across 16 districts of Sakarya over 24 consecutive months, from October 2023 to September 2025. Nine vaccine-dose units were evaluated; a mean of 7,186 (SD = 77.05) FMU-month observations were obtained per unit (pooled n = 64,678). The three coverage measures - total coverage (TC), timely coverage (TMC), and off-schedule ratio (OSR) - are summarized at the unit level in Table 1.

Table 1
Descriptive statistics of coverage measures by vaccine-dose unit (FMU-month level)

Vaccine-dose unit	n	TC (pooled)	TMC (pooled)	OSR	≥ 95% (%)
BCG dose 1	7,143	0.938	0.934	0.005	82.6
HepA dose 1	7,167	0.913	0.906	0.008	76.1
HepA dose 2	7,222	0.906	0.898	0.009	73.9
MMR dose 1	7,163	0.925	0.919	0.007	79.2
MMR dose 2	7,381	0.902	0.891	0.012	71.3
PCV dose 1	7,152	0.938	0.934	0.004	82.5
PCV dose 2	7,134	0.932	0.928	0.004	81.0
PCV booster	7,159	0.923	0.918	0.006	78.5
Varicella dose 1	7,157	0.924	0.918	0.007	78.8

TC = total coverage; TMC = timely coverage; OSR = off-schedule ratio. Pooled = the unit's Σadministered / Σdue; ≥95% = percentage of FMU-months with coverage ≥ 95%. The FMU-month median is 1.000 in all units.

Pooled TC values ranged from 90.2% to 93.8%; the FMU-month median was 100% across all units. The highest pooled values were for BCG dose 1 and PCV dose 1 (93.8%), and the lowest for MMR dose 2 (90.2%) and HepA dose 2 (90.6%). The proportion of FMU-months reaching the ≥ 95% band was 82.6% for BCG dose 1 and 71.3% for MMR dose 2. The pooled off-schedule ratio ranged from 0.4% to 1.2% across all units. The coverage-band composition is presented in Fig. 1.

Service-delivery and district-level determinants

The association of service-delivery- and district-level characteristics with coverage was examined with GLMMs with nested random effects of district/FHC/FMU. The fixed-effect odds ratios (ORs), variance components and fit measures of the pooled models are presented in Table 2; the full OR matrices for each vaccine-dose unit are presented in Tables 3a-c.

Table 3

a. Total coverage (TC) — determinant × unit OR matrix

Determinant	BCG·1	HepA·1	HepA·2	MMR·1	MMR·2	PCV·1	PCV·2	PCV·B	VAR·1	Pooled
Household size	0.86**	0.84**	0.84**	0.84**	0.90	0.88*	0.87*	0.84**	0.84**	0.86**
Mean years of schooling	0.94	0.93	0.92	0.92	0.92	0.92	0.88**	0.92*	0.93	0.90*
Child dependency ratio	1.01	1.02	1.01	1.00	1.00	0.99	0.96	1.00	0.99	0.99
Specialist physician	1.15	1.30**	1.14	1.25*	1.05	1.14	1.20	1.21*	1.21*	1.25*
Physician turnover	0.98	0.99	0.98	0.97	1.00	0.98	0.96	0.96	0.98	0.97
Physician-absent month proportion	0.98	0.98	0.99	1.01	0.95	0.98	0.98	1.01	1.00	1.00
Median FMU population	1.01	0.95	0.95	1.01	1.01	1.02	1.02	1.02	1.02	0.96
Number of FMUs per FHC	0.98	0.93	0.96	0.95	0.94	0.97	0.95	0.96	0.96	0.93
Population CV	0.98	0.92**	0.96	0.99	0.97	0.96	0.98	0.99	0.99	0.97
Season: Winter	1.22*	1.15*	1.06	1.12	0.93	1.30**	1.21**	1.21**	1.15	1.12***
Season: Spring	1.01	1.05	1.00	0.91	0.81***	1.13	1.15	0.96	0.90	0.97
Season: Autumn	1.10	1.07	1.08	1.01	0.89*	1.14	1.22**	1.08	1.03	1.05*

Table 3

b. Timely coverage (TMC) — determinant × unit OR matrix

Determinant	BCG·1	HepA·1	HepA·2	MMR·1	MMR·2	PCV·1	PCV·2	PCV·B	VAR·1	Pooled
Household size	0.87**	0.86**	0.84**	0.86**	0.92	0.88*	0.88*	0.85**	0.86**	0.88*
Mean years of schooling	0.94	0.92*	0.92	0.92*	0.90*	0.91*	0.88**	0.91*	0.92*	0.89**
Child dependency ratio	1.00	1.00	1.00	0.98	0.98	0.98	0.95	0.99	0.98	0.97
Specialist physician	1.13	1.24*	1.11	1.22*	1.07	1.16	1.22*	1.19	1.20*	1.23*
Physician turnover	0.97	0.99	0.98	0.96	1.00	0.96	0.96	0.96	0.96	0.97
Physician-absent month proportion	0.99	0.98	0.99	1.00	0.96	1.00	0.99	1.01	1.00	0.99
Median FMU population	1.02	0.95	0.95	1.02	1.01	1.03	1.01	1.03	1.02	0.98
Number of FMUs per FHC	0.99	0.93	0.96	0.97	0.95	0.96	0.96	0.97	0.97	0.94
Population CV	0.99	0.92**	0.96	0.98	0.95*	0.97	0.99	0.99	0.99	0.98
Season: Winter	1.20*	1.07	1.00	1.07	0.88*	1.23**	1.17*	1.16*	1.10	1.07**
Season: Spring	0.99	1.01	0.98	0.89	0.79***	1.13	1.11	0.94	0.89	0.95*
Season: Autumn	1.08	1.06	1.04	0.99	0.86**	1.13	1.18*	1.04	1.00	1.02

Table 3c. Off-schedule ratio (OSR) — determinant × unit OR matrix

Determinant	BCG·1	HepA·1	HepA·2	MMR·1	MMR·2	PCV·1	PCV·2	PCV·B	VAR·1	Pooled
Household size	1.03	0.97	1.12	0.96	0.89	1.01	1.06	1.10	1.02	0.97
Mean years of schooling	1.08	1.19	1.12	1.16	1.27*	1.26	1.05	1.22	1.19	1.20*
Child dependency ratio	1.18	1.21	0.95	1.31	1.27	1.28	1.23	1.26	1.27	1.23*
Specialist physician	1.06	1.67*	1.29	1.01	0.86	0.61	0.60	0.96	0.94	1.07
Physician turnover	1.15	0.91	1.03	1.10	0.97	1.26*	1.01	1.12	1.23*	1.04
Physician-absent month proportion	0.14	1.10	0.97	1.01	0.90	0.05	0.08	0.98	0.99	0.99
Median FMU population	0.78	1.05	1.04	0.91	0.98	0.84	1.05	0.89	0.91	0.94
Number of FMUs per FHC	0.98	0.97	0.96	0.91	0.92	1.17	0.88	0.94	0.92	0.96
Population CV	0.86	1.15	1.05	1.11	1.21**	0.97	0.90	1.03	1.00	1.05
Season: Winter	1.06	1.73*	1.62*	1.44	1.68**	1.67	1.89	1.70	1.51	1.67***
Season: Spring	1.43	1.53	1.38	1.72*	1.50*	0.90	2.10*	1.71	1.50	1.48***
Season: Autumn	1.24	1.08	1.55*	1.52	1.42	1.06	1.95	1.64	1.52	1.40***

*For Tables 3a–c: each cell is the odds ratio per one-standard-deviation increase in the relevant determinant (continuous variables z-standardised). Asterisks indicate significance: * p < 0.05; ** p < 0.01; *** p < 0.001. 95% CIs for the pooled models are given in Table 2; the choice of distributional family is in Additional file 1: Table S5. The reference for season is summer; specialist physician is binary (reference: none). For OSR columns, OR > 1 increases off-schedule administration (unfavourable). Unit abbreviations: BCG·1 = BCG dose 1; HepA·1/2 = hepatitis A doses 1/2; MMR·1/2 = measles-mumps-rubella doses 1/2; PCV·1/2 = pneumococcal conjugate doses 1/2; PCV·B = PCV booster; VAR·1 = varicella dose 1.*

In the pooled model, a one-standard-deviation increase in household size was negatively associated with the odds of total coverage (OR = 0.87; 95% CI 0.78–0.96; p = 0.008) and timely coverage (OR = 0.88; 95% CI 0.79–0.97; p = 0.011). This association was significant for total coverage in eight of the nine units and was negative in all units; for MMR dose 2, it was of borderline significance (OR = 0.90; p = 0.066) (Table 3a).

In the pooled model, a one-standard-deviation increase in mean years of schooling was negatively associated with timely coverage (OR = 0.89; 95% CI 0.82–0.96; p = 0.004) and positively associated with off-schedule administration (OR = 1.20; 95% CI 1.02–1.40; p = 0.026). For timely coverage, the association was significant in seven of the nine units, whereas for total coverage it was significant in the pooled model and in two units (Tables 3a-c).

The presence of a specialist physician at the FHC was positively associated in the pooled model with total coverage (OR = 1.25; 95% CI 1.04–1.50; p = 0.018) and with timely coverage (OR = 1.23; 95% CI 1.03–1.47; p = 0.022); it was independently significant in four of the nine units (Table 3a,b).

The child dependency ratio was positively associated only with off-schedule administration (OR = 1.23; 95% CI 1.00-1.51; p = 0.049); it showed no significant association with total or timely coverage. Physician turnover, physician-absent month proportion, number of FMUs per FHC and median FMU population were not significant in the pooled coverage models. Variability in FMU population (population CV) was not significant in the pooled model but was significant for the HepA dose 1 and MMR dose 2 units (Tables 3a-c).

Season (reference: summer) was associated with coverage. Total coverage was higher in winter in the pooled model (OR = 1.12; 95% CI 1.07–1.17; p < 0.001), and this association was significant in five of the nine units. Off-schedule administration was higher in all three non-summer seasons (winter OR = 1.67; spring OR = 1.48; autumn OR = 1.40; all p < 0.001).

Most of the variance was at the FMU level. In the pooled total-coverage model, the total intraclass correlation (ICC) was 0.086 (FMU level 5.9%; FHC 1.8%; district ~ = 0%; vaccine-dose unit 0.9%); the marginal R^2 was 0.031 and the conditional R^2 was 0.261. In the off-schedule model the ICC was 0.201. The variance components, ICC, Nakagawa R^2 values and fit measures of the three pooled models are given in the lower part of Table 2.

Spatial findings

Geographic clustering at the FHC level was examined using the k = 3 nearest-neighbor criterion (Table 4). Global Moran's I was significant for only one of the nine units, HepA dose 2 (I = 0.150; p = 0.013); the other eight units and the pooled analysis were not significant. For HepA dose 2 at k = 3, the local Moran (LISA) analysis identified three high-high (hot-spot) clusters and no significant low-low (cold-spot) cluster (Fig. 2). The Pearson correlation between isolation (distance to nearest neighbor) and coverage ranged from 0.12 to 0.21 across all units.

Table 4
Spatial autocorrelation and local clustering by vaccine-dose unit (k = 3)

Vaccine-dose unit	Moran's I	p	LL	HH	Isol. r
BCG dose 1	—	0.747	2	0	0.125
HepA dose 1	0.102	0.063	1	4	0.136
HepA dose 2	0.150	0.013*	0	3	0.214
MMR dose 1	0.073	0.121	2	0	0.147
MMR dose 2	—	0.495	1	0	0.197
PCV dose 1	—	0.689	2	0	0.121
PCV dose 2	0.030	0.290	1	2	0.175
PCV booster	0.056	0.209	1	0	0.176
Varicella dose 1	0.085	0.092	2	1	0.154
All (pooled, 9 units)	0.066	0.137	0	0	0.190

*Moran's I: Monte Carlo test with 999 permutations. LL = number of low-low (cold-spot) local clusters; HH = number of high-high (hot-spot) local clusters; Isol. r = Pearson correlation of isolation × coverage. * p < 0.05. '—': Moran's I not reported for non-significant permutation results. Neighbourhood sensitivity (k = 4, k = 5) is given in Additional file 1: Table S4.*

Sensitivity to the neighborhood definition was assessed using the k = 4 and k = 5 criteria. HepA dose 2 remained significant under all three neighborhood criteria (k = 4, p = 0.024; k = 5, p = 0.004); HepA dose 1 and varicella dose 1 were significant only at k = 5 (p = 0.028 and p = 0.047, respectively) (Additional file 1: Table S4).

Discussion

In this study, first-line childhood vaccination performance in Sakarya Province was examined at three levels simultaneously, following the true hierarchy of the data: 16 districts, 99 family health centres (FHCs) and 349 family medicine units (FMUs). The analysis is based on 64,678 FMU-month observations and nine vaccine-dose units. Pooled total coverage ranged from 90.2% to 93.8%; by contrast, the proportion of FMU-months reaching the ≥ 95% band remained between 71.3% and 82.6%. Off-schedule administration was generally low (0.4–1.2%).

In the multivariable mixed models, the strongest and most consistent determinant was household size. The effect of mean years of schooling took an unexpected form: it affected total coverage only to a limited extent, while it markedly reduced timely coverage and increased off-schedule administration. The presence of a specialist physician at the FHC was positively associated with coverage. Physician turnover, physician-absent month proportion and structural unit variables were not significant. Most of the variance was concentrated at the FMU level; the FHC level accounted for a smaller share, and the contribution of the district level was close to zero. Spatial clustering was detected in only one of the nine units. These findings are discussed in turn below.

The pooled coverage values appear high at first glance. However, the fact that pooled ratios remain around 90% despite an FMU-month median of 100% indicates that the distribution is markedly skewed. What pulls the dose-weighted average down is a limited number of poorly performing unit-months. This points not to a widespread deficiency across the province but to a targetable gap concentrated in specific unit-months.

Measles-mumps-rubella (MMR) dose 2 is of particular importance in this respect. This unit has both the lowest pooled coverage (90.2%) and the lowest proportion in the > = 95% band (71.3%). Measles elimination and the maintenance of

herd immunity require > = 95% coverage with two doses of measles-containing vaccine, not only nationally but in every sub-region(8, 34). Studies of the immunity threshold adjusted for contact patterns likewise point to achieving 95% immunity by five years of age and maintaining it at older ages(7). Although coverage appears adequate across the sample as a whole, the fact that roughly one third of unit-months fall below the threshold for MMR dose 2 is a risk that must be monitored.

A one-standard-deviation increase in mean household size reduced the odds of total and timely coverage by approximately 12–13% in the pooled model (TC OR = 0.87; TMC OR = 0.88). This association was significant for total coverage in eight of the nine units and was in the same direction across all nine. No other determinant showed this level of consistency.

The finding aligns strongly with the individual-level literature. In creche children in Athens, the likelihood of receiving all vaccines fell as household size increased(35). In Ethiopia, a family size of five or more more than doubled the odds of incomplete immunization(36). In Canada's national immunization survey, the number of children in the household was associated with both vaccine hesitancy and refusal(37). In the Netherlands, coverage declined more rapidly in families with four or more children(38).

The mechanisms that might explain this pattern are clear. In crowded households, the parental time and resources available per child decrease, and taking more than one child to the same appointment creates a logistical burden. A comprehensive review of reasons for missed primary care appointments found that competing demands and priorities are among the principal factors(39). It should be noted that the finding was obtained at the ecological level; nevertheless, the consistency across units supports the robustness of the association. In regions where large family structures are common, household-based reminders, home visits and multi-child appointment arrangements may offer a feasible intervention lever.

The behaviour of the education variable becomes clear when the three outcome measures are examined separately. For total coverage, although the pooled effect is significant (OR = 0.90), it is significant at the unit level in only two vaccine-doses (PCV dose 2 and PCV booster). For timely coverage, the picture changes: the pooled effect is stronger (OR = 0.89) and is significant in seven of the nine units. For off-schedule administration, the direction reverses, and the pooled OR rises to 1.20; the OR exceeds one in all nine units.

Read together, these three patterns yield the following conclusion: in districts with high education levels, children are vaccinated, but not at the time prescribed by the schedule. That is, what is at stake is not a loss of coverage but a systematic shift in timing in favour of off-schedule administration. That the effect on total coverage appears in only two units supports this interpretation; had the underlying phenomenon been vaccine avoidance, the effect would have been expected to appear widely in total coverage as well.

The international literature is consistent with this reading. In a study covering more than 14 million participants from 90 countries, vaccine hesitancy was more common in less-educated groups, whereas vaccine refusal was higher in more-educated groups, and this divergence was particularly pronounced in high-income countries(40). In a national study of 3,927 parents in France, the likelihood that highly educated parents belonged to the vaccine-delaying group was markedly increased (AOR = 1.73); the same study showed that this association operated through trust in the health system and concern about 'making the right decision'(41). In Argentina, high maternal education was significantly associated with vaccine hesitancy (OR = 2.66)(42). In a study of 2,054 parents in China, hesitancy was also more frequent among more highly educated parents(43). An umbrella review bringing together 26 systematic reviews shows that the association between education and vaccine uptake does not operate in the same direction across all contexts and that inverse associations are frequently reported, particularly in high-income countries(22).

Why this association is reflected in timing rather than coverage also finds support in the literature. In a meta-analysis of 46 studies, the association of vaccine hesitancy with delaying vaccination (OR = 2.61) was markedly stronger than its association with never being vaccinated (OR = 1.48)(44). In other words, hesitancy is expressed mostly as delay rather than refusal. Its concrete form is alternative vaccination schedules: in the United States, about 13% of parents reported following a schedule different from the recommended one, and more than half of these delayed some vaccines to older ages(45). A qualitative study with high-socioeconomic-status parents who identified as pro-vaccine showed that this group did not refuse vaccines but frequently delayed them and spread doses over time(46). Calls for timeliness and coverage to be monitored as separate measures also rest on these findings(16). It is accepted that vaccine hesitancy is not specific to a single socioeconomic profile and is also shaped by contextual, vaccine-specific factors(47).

The Turkish data require a careful reading here. Vaccine hesitancy was detected in 32% of 350 parents presenting to family health centres in Mardin(32). On the other hand, studies also exist in which vaccine hesitancy decreases as socioeconomic status and education level rise(33, 48). In a nationwide study of 245 academics working at public universities, hesitancy was shown not to disappear entirely even in this group with high access to scientific sources(49). A qualitative study examining vaccine refusal in Türkiye revealed that decisions are shaped by institutional distrust and by alternative information sources such as the internet, social media and books(50).

This picture makes an important point clear: Türkiye's individual-level data indicate that hesitancy decreases as education rises. Our finding therefore cannot be explained by a simple 'educated parents are hesitant' assumption. Moreover, our variable is the district mean, not individual education; the two measurements lie on different levels, and an association at the ecological level cannot be translated directly into individual behavior. Nevertheless, the pattern our data reveal - coverage preserved, timing shifted - is consistent with the 'hesitancy manifests as delay' mechanism in the international literature. In districts with high education levels, factors such as working hours, service-use preferences, and recourse to private health facilities may also influence timing. This interpretation is not causal but hypothesis-generating, and it contains the following testable prediction: in individual-level data, children living in high-education districts should show a significant delay in the ages at which doses are received, while their final coverage remains similar.

In the pooled model, the presence of a specialist physician at the FHC was positively associated with both total coverage (OR = 1.25) and timely coverage (OR = 1.23); this association was independently significant in four of the nine units. The finding is consistent with the literature linking a qualified health workforce to coverage. In a study of 1,346 health sub-centers in India, facility quality was positively associated with both full immunization and timely vaccination(23). The provider's attitude towards vaccines has also been shown to directly affect the timing of a child's vaccination: in a study in Switzerland examining 1,256 parents and 112 physicians together, the odds of non-timely vaccination were markedly increased in children seen by hesitant physicians(25). Similarly, physicians' area of specialty and the training they have received alter the way they deliver vaccine recommendations(51). That health-workforce capacity is one of the long-term determinants of coverage has also been reported in large-scale studies(52).

The presence of a specialist physician may not be a cause in itself. This variable may also serve as a marker for centers with better resource allocation, or for relatively urban or institutionally higher-capacity centers. These data do not distinguish whether the contribution is direct or indirect.

In the study, the child dependency ratio was associated only with off-schedule administration (OR = 1.23); no effect was detected on total or timely coverage. This selective pattern suggests that the child population burden does not reduce coverage but strains timing. It is known that service-delivery and health-worker factors are decisive in missed vaccination opportunities. (53). In a multilevel study conducted at ten different primary-care facilities in Kano, Nigeria, the principal determinants of missed vaccination opportunities were associated with the facility's workflow and mode

of presentation(54). It has been shown that in settings where demand exceeds capacity, services adapt through prioritisation and flexing, which is reflected in timing(55). In districts with a dense child population, the difficulty of appointment capacity in meeting demand may explain the increase in off-schedule administration.

The physician-absent month proportion denotes months when the FMU has no salaried physician, and the service is carried out by proxy through another unit in the same FHC or the nearest FHC. This variable was not significant for any of the three outcome measures. However, interpreting this result as 'no effect' would be misleading. Only five FMU-months across the entire study period were recorded as physician-absent. Given such a rare exposure, a statistically significant association cannot be expected.

Physician turnover, number of FMUs per FHC, median FMU population, and population variability over the study period were also not significant in the pooled coverage models. It is well documented that physician turnover in primary care disrupts continuity of care and adversely affects patient experience(56). By contrast, in a large American cohort, physician turnover worsened patient experience but largely did not affect ambulatory quality-of-care indicators(57). A service such as vaccination - strongly protocol-bound, standardised and supported by reminder-recall systems - may be expected to be relatively resistant to physician-level fluctuations. In this respect the finding may be regarded as a positive sign of resilience, indicating that the family medicine system can sustain vaccination services independently of individual-physician continuity. Even so, the significance of physician turnover in some units in the off-schedule models shows that the subtler effects of continuity on timing should not be overlooked.

Total coverage was higher in winter than in summer (OR = 1.12). Off-schedule administration, in turn, was markedly increased in all three non-summer seasons (winter OR = 1.67; spring OR = 1.48; autumn OR = 1.40). This pattern is likely to be operational rather than biological. In summer, holidays, travel and reduced routine contact with health facilities may affect both planned presentations and timing, creating a different pattern in the summer reference period. The literature on the seasonality of routine childhood vaccines is limited. By contrast, it has been clearly shown, in pandemic-related interruptions, that periods disrupting service access impair coverage and timing(58). For this reason, intensifying reminder-recall activities during the summer period would be appropriate.

In the pooled total-coverage model, the overall intraclass correlation was low (ICC = 0.086). The distribution of this value across levels shows that variability is concentrated at the lowest rung of the hierarchy. The FMU level accounted for 5.9% of the total variance, the FHC level 1.8%, and the vaccine-dose unit 0.9%, while the district-level variance was close to zero. Coverage differences arise not between districts but between units within the same district and, largely, within the same center.

This pattern stands in marked contrast to findings from community-based systems. In a multilevel study of timely full immunization in north-western Ethiopia, 26% of variability was between communities(59), whereas the corresponding share here is about one third of that. It may be said that the registered-population-based family medicine model largely suppresses differences between geographical units but does not eliminate heterogeneity at the unit level. This picture, favourable in terms of geographical equity, indicates that monitoring and intervention should be structured at the unit rather than the district level. Measuring at which level clustering arises is the established way of assessing the magnitude of contextual effects(29).

The low total ICC also indicates that, alongside between-unit differences, within-unit fluctuation is large; the same FMU varies markedly across months and vaccine-doses. The variance explained by the fixed effects, in turn, is limited (marginal $R^2 = 0.031$). The measured service-delivery- and district-level variables account for only a small part of the differences in coverage. The source of this residual variability cannot be determined with the data at hand. Possible candidates include individual parental attitudes, household-level barriers and differences in units' reminder-recall practices; however, these are untested hypotheses.

The total ICC was about 2.3 times higher for off-schedule administration than for total coverage (0.201 vs 0.086), indicating that timing problems are more clustered across units. While coverage converges toward a common standard, whether doses are administered on schedule appears more dependent on the unit's entrenched practice. For this reason, off-schedule administration may serve as a more discriminating indicator than coverage for unit-targeted monitoring.

Global spatial autocorrelation was significant for only one of the nine units, HepA dose 2, and this result was consistent across the k = 3, 4, and 5 neighborhood definitions. No significant clustering was detected in the other eight units or in the pooled analysis. The correlation between isolation and coverage was also weak (0.12–0.21). Taken together with the low district-level variance, this indicates that coverage is distributed largely homogeneously in space.

This result should be read not as a 'negative finding' but as evidence of the geographical equity of service delivery. Studies conducted with population-based surveys in low- and middle-income countries generally report strong spatial clustering and marked sub-regional heterogeneity(9, 60). Low-coverage local clusters can be detected even in countries with high national coverage(12). The absence of such clustering in Sakarya may reflect the geographical consistency of a mature, registered-population-based primary-care system. The finding aligns with a Brazilian study likewise conducted with national immunization-programme administrative data that detected no global autocorrelation(61). The exceptional clustering in HepA dose 2, in turn, should be regarded as a limited pattern arising from local supply or administration.

Strengths and limitations

The principal strength of the study is that it covers province-wide data (349 FMUs, 64,678 FMU-months). The modelling reflects the true hierarchy of the data (district/FHC/FMU) and includes a crossed random intercept for vaccine-dose units. The distributional family was determined separately for each model on the basis of overdispersion diagnostics and was supported by DHARMa, VIF and spatial-residual analyses. The consistency of associations was assessed with both pooled and unit-specific models. Treating timeliness and off-schedule administration as separate outcomes alongside coverage provides a richer picture of performance than studies focusing on coverage alone; indeed, delayed vaccination increases risk by prolonging the window of susceptibility(62).

Beyond its methodological strengths, the study's scope also holds distinctive value for health management. The analysis covers the province's entire first-line childhood vaccination service: all 16 districts, all 99 FHCs, and all 349 FMUs were included through complete enumeration rather than sampling. This scope yields a performance map free of representation problems and directly convertible into managerial decisions. Monitoring the entire primary care system over a consecutive 24-month window, across nine vaccine-dose units and three outcome measures, provides a comprehensive scope and level of detail rarely encountered in the field.

The managerial value of the findings stems from the nature of the determinants. Household size is a demand-side indicator computable from routine administrative records; it is therefore suitable for direct risk profiling in the field, and units where crowded households are concentrated can be identified in advance. The positive association of the presence of a specialist physician with coverage, in turn, defines a directly actionable lever on the supply side; workforce planning and assignment decisions can be based on this finding. The study's outputs thus offer practical guidance for risk profiling and intervention efficiency in primary health-care management aimed at increasing vaccine coverage.

This approach is also consistent with the established targeted-planning tradition in immunization programmes. The 'Reaching Every District' approach developed by WHO and UNICEF envisages using coverage data to analyse the distribution of unvaccinated children and to prioritise poorly performing administrative units(27). Our findings show

that this logic should be moved one rung down: in Sakarya, the unit to be prioritised is the FMU, not the district. Georeferenced microplanning has been shown to increase coverage(63), and targeted planning to be cost-effective relative to the traditional approach(64). This framework, which aims to deliver the right intervention to the right population at the right time, is the fundamental way of increasing efficiency under resource constraints(65).

The findings should be interpreted in the light of several limitations. First, the study is ecological and registry-based; the denominators rely on the information system's counts of 'children due for vaccination', and administrative coverage may be biased relative to field surveys or serological measurements. Second, because the socioeconomic and demographic determinants were defined at the district level (n = 16), resolution and power are limited. This increases the risk of ecological fallacy. Third, the cross-sectional and retrospective design does not permit causal inference. Fourth, some exposures such as the physician-absent month proportion were so rare in the dataset that effect estimation could not be performed for these variables. Fifth, the analysis is limited to the nine antigens not included in combination vaccines; because the diphtheria, pertussis, tetanus, polio, hepatitis B and Hib components were excluded, the findings cannot be generalised directly to these vaccines. Finally, because individual parental-level factors (attitudes, hesitancy, income, migration status) could not be measured, the possibility of confounding remains.

Within the scope of this study, the FHCs requiring priority intervention were identified through LISA clustering and shared with the Provincial Health Directorate for targeted microplanning.

Conclusions

First-line childhood vaccination coverage in Sakarya is generally high and geographically equitable. Nevertheless, a significant minority of unit-months, particularly for the second doses of MMR and hepatitis A, remain below the ≥ 95% threshold. That most of the variability in vaccine coverage is concentrated at the smallest service-unit (FMU) level and that no spatial clustering is present indicate that targeted micro-interventions focused on poorly performing FMUs will be more effective than interventions spread across the whole province.

Three findings stand out for policy. First, household size is the most consistent determinant and calls for strengthening reminder-recall systems in regions where crowded households are common. Second, the effect of education level appears not in coverage but in timing; this necessitates a monitoring approach focused on timing rather than information provision in highly educated regions. Third, and the most directly actionable from a managerial standpoint, the presence of a specialist physician at the FHC markedly increases both total and timely coverage (TC OR = 1.25; TMC OR = 1.23). This finding shows that workforce planning can be regarded as an immunization-performance tool in its own right: assigning specialist physicians with an eye to low-coverage centres carries the potential to raise coverage even within the existing staffing structure. That physician turnover and staffing fluctuations did not adversely affect coverage is reassuring in terms of system resilience. Continuous monitoring of timely coverage and off-schedule administration as routine quality indicators, the development of catch-up strategies for the summer period, and the establishment of unit-level feedback mechanisms are recommended.

Abbreviations

AOR
adjusted odds ratio
BCG
Bacillus Calmette-Guerin
CI
confidence interval

CV
coefficient of variation
DTP
diphtheria-tetanus-pertussis
FHC
family health centre
FMU
family medicine unit
GLMM
generalised linear mixed model
HepA
hepatitis A
Hib
Haemophilus influenzae type b
IA2030
Immunization Agenda 2030
ICC
intraclass correlation coefficient
LISA
local indicators of spatial association
LRT
likelihood-ratio test
MMR
measles-mumps-rubella
OR
odds ratio
OSR
off-schedule ratio
PCV
pneumococcal conjugate vaccine
PHD
Provincial Health Directorate
SD
standard deviation
SEGE
Socioeconomic Development Ranking
TC
total coverage
TMC
timely coverage
TurkStat
Turkish Statistical Institute
VAR
varicella
VIF
variance inflation factor

WHO
World Health Organization
WUENIC
WHO/UNICEF Estimates of National Immunization Coverage.

Declarations

Ethics approval and consent to participate

Approval for the study was obtained from the Scientific Research Ethics Committee of Health Sciences, Faculty of Medicine, Sakarya University (decision date 20 September 2025, no. E-43012747-050.04-513197-479). Because the study was retrospective and used aggregated administrative data containing no personal identifiers, the requirement for informed consent was waived by the same committee. All methods were performed in accordance with the relevant guidelines and regulations, in line with the Declaration of Helsinki.

Consent for publication

Not applicable.

Availability of data and materials

The analysis code and the analysis tool (an R/Shiny application) developed and used in this study are publicly available in the Aperta (ULAKBIM) repository: https://aperta.ulakbim.gov.tr/records/292895 (access token: eyJhbGciOiJIUzUxMiJ9.eyJpZCI6ImYyMWYz ODk0LWYyMjYtNDU4OC04MjhjLTMzYzA3Y2 UzNDFjMyIsImRhdGEiOnt9LCJyYW5kb20iOiJ iNDViODVhNDhmZDM3Yjc3ZGI5OGExYjRm ZWE4ZDdmZSJ9.F9r7bEyl-RTsqiQdRHAyRFHHmTSlKePF4xRwc87SADYXA b0S91YRIHgVvNoRBsSh9N0R1pdun1m3dQSju lfPJQ). The datasets analysed during the current study are available from the corresponding author on reasonable request, subject to the permission of the Sakarya Provincial Health Directorate.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

EK and AU: study design, preparation of the data for analysis, development of the analysis tool, and drafting of the manuscript. EA: acquisition of the data from the Provincial Health Directorate. STÇ and KÖ: study design, data acquisition, and proofreading. All authors read and approved the final manuscript.

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References

1. Haeuser E, Byrne S, Nguyen J, Raggi C, McLaughlin SA, Bisignano C. vd. Global, regional, and national trends in routine childhood vaccination coverage from 1980 to 2023 with forecasts to 2030: a systematic analysis for the Global Burden of Disease Study 2023. Lancet 19 Temmuz. 2025;406(10500):235–60. 10.1016/S0140-6736(25)01037-2.
2. UNICEF. Childhood immunization continues to recover across Europe and Central Asia, but gaps remain – UNICEF [Internet]. 2026 [a.yer 24 Temmuz 2026]. Erişim adresi: https://www.unicef.org/eca/press-releases/childhood-immunization-continues-recover-across-europe-and-central-asia-gaps-remain
3. WHO. Global childhood immunization coverage inches forward despite conflict and hesitancy – UNICEF, WHO [Internet]., 2026 [a.yer 24 Temmuz 2026]. Erişim adresi: https://www.who.int/news/item/15-07-2026-global-childhood-immunization-coverage-inches-forward-despite-conflict-and-hesitancy---unicef--who
4. Jones CE. Routine Vaccination Coverage — Worldwide, 2023. MMWR Morb Mortal Wkly Rep. 2024;73. 10.15585/mmwr.mm7343a4
5. WHO. European Region reports highest number of measles cases in more than 25 years – UNICEF, WHO/Europe [Internet]., 2025 [a.yer 24 Temmuz 2026]. Erişim adresi: https://www.who.int/europe/news/item/13-03-2025-european-region-reports-highest-number-of-measles-cases-in-more-than-25-years---unicef--who-europe
6. WHO. Measles cases dropped in Europe and Central Asia in 2025 compared to the previous year, but the risk of outbreaks remains – UNICEF and WHO [Internet]. 2026 [a.yer 24 Temmuz 2026]. Erişim adresi: https://www.who.int/europe/news/item/11-02-2026-measles-cases-dropped-in-europe-and-central-asia-in-2025-compared-to-the-previous-year--but-the-risk-of-outbreaks-remains---unicef-and-who
7. Funk S, Knapp JK, Lebo E, Reef SE, Dabbagh AJ, Kretsinger K. vd. Combining serological and contact data to derive target immunity levels for achieving and maintaining measles elimination. BMC Med. 25 Eylül 2019;17(1):180. 10.1186/s12916-019-1413-7
8. Minta AA, Ferrari M, Antoni S, Lambert B, Sayi TS, Hsu CH. vd. Progress Toward Measles Elimination — Worldwide, 2000–2023. Morb Mortal Wkly Rep. 2024;73:1036–42. 10.15585/mmwr.mm7345a4.
9. Dimitrova A, Carrasco-Escobar G, Richardson R, Benmarhnia T. Essential childhood immunization in 43 low- and middle-income countries: Analysis of spatial trends and socioeconomic inequalities in vaccine coverage. PLOS Med. 2023;20. 10.1371/journal.pmed.1004166.
10. Eze P, Agu UJ, Aniebo CL, Agu SA, Lawani LO, Acharya Y. Factors associated with incomplete immunisation in children aged 12–23 months at subnational level, Nigeria: a cross-sectional study [Internet]. 01 Haziran. 2021. 10.1136/bmjopen-2020-047445
11. Nguyen PT, Nakamura R, Shimadzu H, Abubakar AK, Le PM, Nguyen HV. vd. Progress and inequality in child immunization in 38 African countries, 2000–2030: A spatio-temporal Bayesian analysis at national and sub-national levels. PLOS Med 29 Temmuz. 2025;22(7):e1004664. 10.1371/journal.pmed.1004664.
12. Brownwright TK, Dodson ZM, van Panhuis WG. Spatial clustering of measles vaccination coverage among children in sub-Saharan Africa. BMC Public Health 15 Aralık. 2017;17(1):957. 10.1186/s12889-017-4961-9.
13. Maïga A, Jiwani SS, Mutua MK, Porth TA, Taylor CM, Asiki G. vd. Generating statistics from health facility data: the state of routine health information systems in Eastern and Southern Africa. BMJ Glob Health 29 Eylül. 2019;4(5). 10.1136/bmjgh-2019-001849. PubMed PMID:.
14. Fadnes LT, Nankabirwa V, Sommerfelt H, Tylleskär T, Tumwine JK, Engebretsen IMS. Is vaccination coverage a good indicator of age-appropriate vaccination? A prospective study from Uganda. Vaccine 27 Nisan. 2011;29(19):3564–70. 10.1016/j.vaccine.2011.02.093.
15. Stein-Zamir C, Israeli A. Timeliness and completeness of routine childhood vaccinations in young children residing in a district with recurrent vaccine-preventable disease outbreaks, Jerusalem, Israel. Eurosurveillance. 07 Şubat.

2019;24(6):1800004. 10.2807/1560-7917.ES.2019.24.6.1800004

16. Freeman RE, Thaker J, Daley MF, Glanz JM, Newcomer SR. Vaccine timeliness and prevalence of undervaccination patterns in children ages 0–19 months. Vaccine 31 Ocak. 2022;40(5):765–73. 10.1016/j.vaccine.2021.12.037. U.S., National Immunization Survey-Child 2017.
17. Dayan GH, Shaw KM, Baughman AL, Orellana LC, Forlenza R, Ellis A. vd. Assessment of Delay in Age-appropriate Vaccination Using Survival Analysis. Am J Epidemiol 15 Mart. 2006;163(6):561–70. 10.1093/aje/kwj074.
18. Wariri O, Utazi CE, Okomo U, Sogur M, Murray KA, Grundy C. vd. Timeliness of routine childhood vaccination among 12–35 months old children in The Gambia: Analysis of national immunisation survey data, 2019–2020. PLOS ONE 21 Temmuz. 2023;18(7):e0288741. 10.1371/journal.pone.0288741.
19. Dolan SB, Carnahan E, Shearer JC, Beylerian EN, Thompson J, Gilbert SS. vd. Redefining vaccination coverage and timeliness measures using electronic immunization registry data in low- and middle-income countries. Vaccine 22 Mart. 2019;37(13):1859–67. 10.1016/j.vaccine.2019.02.017.
20. Memon M, Siddiqi D, Dharma V, Shah M, Iftikhar S, Setayesh H. vd. Coverage, timeliness of measles immunisation and its predictors in Pakistan: an analysis of 6.2 million children enrolled in the Provincial Electronic Immunisation Registry. BMJ Glob Health. 2025;10. 10.1136/bmjgh-2024-016717.
21. Williams SV, Akande T, Abbas K. Systematic review of social determinants of childhood immunisation in low- and middle-income countries and equity impact analysis of childhood vaccination coverage in Nigeria. PLOS ONE 06 Mart. 2024;19(3):e0297326. 10.1371/journal.pone.0297326.
22. Sacre A, Bambra C, Wildman JM, Thomson K, Bennett N, Sowden S. vd. Socioeconomic inequalities in vaccine uptake: A global umbrella review. PLOS ONE. 13 Aralık 2023;18(12):e0294688. 10.1371/journal.pone.0294688
23. Summan A, Nandi A, Schueller E, Laxminarayan R. Public health facility quality and child immunization outcomes in rural India: A decomposition analysis. Vaccine 06 Nisan. 2022;40(16):2388–98. 10.1016/j.vaccine.2022.03.017.
24. Eboreime E, Abimbola S, Bozzani F. Access to Routine Immunization: A Comparative Analysis of Supply-Side Disparities between Northern and Southern Nigeria. PLOS ONE. 21 Aralık. 2015;10(12):e0144876. 10.1371/journal.pone.0144876
25. Jafflin K, Deml MJ, Schwendener CL, Kiener L, Delfino A, Gafner R. vd. Parental and provider vaccine hesitancy and non-timely childhood vaccination in Switzerland. Vaccine. 20 Mayıs 2022;40(23):3193 – 202. 10.1016/j.vaccine.2022.04.044
26. Blanc DC, Grundy J, Sodha SV, O'Connell TS, von Mühlenbrock HJM, Grevendonk J. vd. Immunization programs to support primary health care and achieve universal health coverage. Vaccine 08 Nisan 2024;The Immun Agenda 203042:S38–42. 10.1016/j.vaccine.2022.09.086
27. Vandelaer J, Bilous J, Nshimirimana D. Reaching Every District (RED) approach: a way to improve immunization performance. Bull World Health Organ Mart. 2008;86(3):A–B. 10.2471/BLT.07.042127 . PubMed PMID: 18368190; PubMed Central PMCID: PMC2647411.
28. Austin PC, Merlo J. Intermediate and advanced topics in multilevel logistic regression analysis. Stat Med. 2017;36(20):3257–77. 10.1002/sim.7336.
29. Merlo J, Chaix B, Yang M, Lynch J, Råstam L. A brief conceptual tutorial of multilevel analysis in social epidemiology: linking the statistical concept of clustering to the idea of contextual phenomenon. J Epidemiol Community Health 01 Haziran. 2005;59(6):443–9. 10.1136/jech.2004.023473 . PubMed PMID: 15911637.
30. Cullu F, Vural M. An Overview on Child Health Care in Turkey. J Pediatr. 01 Ekim 2016;Diversity of Child Health Care in Europe: A Study of the European Paediatric Association/Union of National European Paediatric Societies and Associations177:S213-6. 10.1016/j.jpeds.2016.04.057

31. Espinosa-González AB, Normand C. Challenges in the implementation of primary health care reforms: a qualitative analysis of stakeholders' views in Turkey [Internet]. 01 Temmuz 2019. 10.1136/bmjopen-2018-027492
32. BAYRAM DEĞER V YİĞİTALPG. Level of hesitation of parents about childhood vaccines and affecting factors: a cross-sectional study in Turkey. BMC Public Health 13 Eylül. 2024;24(1):2494. 10.1186/s12889-024-19961-1.
33. Durmuş Sarıkahya S, Güden E, Sümeyye Yorulmaz D. Childhood vaccine hesitancy in two regions with different socioeconomic backgrounds in Turkey. J Public Health 01 Mayıs. 2024;32(5):737–46. 10.1007/s10389-023-01854-z.
34. Gastañaduy PA, Goodson JL, Panagiotakopoulos L, Rota PA, Orenstein WA, Patel M. Measles in the 21st Century: Progress Toward Achieving and Sustaining Elimination. J Infect Dis 01 Ekim. 2021;224(Supplement4):S420–8. 10.1093/infdis/jiaa793.
35. Pavlopoulou ID, Michail KA, Samoli E, Tsiftis G, Tsoumakas K. Immunization coverage and predictive factors for complete and age-appropriate vaccination among preschoolers in Athens, Greece: a cross- sectional study. BMC Public Health 02 Ekim. 2013;13(1):908. 10.1186/1471-2458-13-908.
36. Kebede SA, Tsega Y, Cherie N, Molla A, Stecher C. Determinants of incomplete immunization among 12–23 months old children in Ethiopia: A multilevel analysis. PLOS ONE 29 Nisan. 2025;20(4):e0321947. 10.1371/journal.pone.0321947.
37. Chen R, Guay M, Gilbert NL, Dubé E, Witteman HO, Hakim H. Determinants of parental vaccine hesitancy in Canada: results from the 2017 Childhood National Immunization Coverage Survey. BMC Public Health 24 Kasım. 2023;23(1):2327. 10.1186/s12889-023-17079-4.
38. Pijpers J, van Roon A, Schipper M, Stok M, Hof S, van van den, Gaalen R. The decrease in childhood vaccination coverage and its sociodemographic determinants, the Netherlands, birth cohorts 2008 to 2020. Euro 02 Ekim. 2025;30(39):2500251. 10.2807/1560-7917.ES.2025.30.39.2500251.
39. Lindsay C, Baruffati D, Mackenzie M, Ellis DA, Major M, O'Donnell CA. vd. Understanding the causes of missingness in primary care: a realist review. BMC Med 10 Haziran. 2024;22(1):235. 10.1186/s12916-024-03456-2.
40. Bergen N, Kirkby K, Fuertes CV, Schlotheuber A, Menning L, Mac Feely S. vd. Global state of education-related inequality in COVID-19 vaccine coverage, structural barriers, vaccine hesitancy, and vaccine refusal: findings from the Global COVID-19 Trends and Impact Survey. Lancet Glob Health 01 Şubat. 2023;11(2):e207–17. 10.1016/S2214-109X(22)00520-4.
41. Bocquier A, Fressard L, Cortaredona S, Zaytseva A, Ward J, Gautier A, vd. Social differentiation of vaccine hesitancy among French parents and the mediating role of trust and commitment to health: A nationwide cross-sectional study. Vaccine 29 Kasım. 2018;36(50):7666–73. 10.1016/j.vaccine.2018.10.085 . PubMed PMID: 30391054.
42. Gentile A, Pacchiotti AC, Giglio N, Nolte MF, Talamona N, Rogers V. vd. Vaccine hesitancy in Argentina: Validation of WHO scale for parents. Vaccine 30 Temmuz. 2021;39(33):4611–9. 10.1016/j.vaccine.2021.06.080.
43. Tang S, Liu X, Jia Y, Chen H, Zheng P, Fu H. vd. Education level modifies parental hesitancy about COVID-19 vaccinations for their children. Vaccine 09 Ocak. 2023;41(2):496–503. 10.1016/j.vaccine.2022.11.060.
44. Yang X, Shi N, Liu C, Zhang J, Miao R, Jin H. Relationship between vaccine hesitancy and vaccination behaviors: Systematic review and meta-analysis of observational studies. Vaccine 12 Ocak. 2024;42(2):99–110. 10.1016/j.vaccine.2023.11.051.
45. Dempsey AF, Schaffer S, Singer D, Butchart A, Davis M, Freed GL. Alternative Vaccination Schedule Preferences Among Parents of Young Children. Pediatr 01 Kasım. 2011;128(5):848–56. 10.1542/peds.2011-0400.
46. Wang E, Baras Y, Buttenheim AM. Everybody just wants to do what's best for their child: Understanding how pro-vaccine parents can support a culture of vaccine hesitancy. Vaccine 27 Kasım. 2015;33(48):6703–9. 10.1016/j.vaccine.2015.10.090.

47. MacDonald NE. Vaccine hesitancy: Definition, scope and determinants. Vaccine. 14 Ağustos 2015;WHO Recommendations Regarding Vaccine Hesitancy33(34):4161–4. 10.1016/j.vaccine.2015.04.036
48. Çelik E, Şahin ÇE, Değer MS, Altaş ZM. Vaccine hesitation: attitudes of Turkish health worker parents towards adult and childhood immunisation. BMC Public Health 20 Ağustos. 2025;25(1):2857. 10.1186/s12889-025-24100-5.
49. Palloş A, Yüksel Kaçan C. Childhood vaccine hesitancy among academics in Türkiye. BMC Public Health 03 Kasım. 2025;25(1):3757. 10.1186/s12889-025-24976-3.
50. Uğrak U, Aksungur A, Akyüz S, Şen H, Seyhan F. Understanding the rise of vaccine refusal: perceptions, fears, and influences. BMC Public Health 29 Temmuz. 2025;25(1):2574. 10.1186/s12889-025-23754-5.
51. Ilyasova AA, Queen TL, Gilkey M, Fogel BN, Odebunmi OO, Yanguela J. vd. Use of presumptive recommendations and other strategies to encourage HPV vaccine uptake: Results from a national survey of primary care health professionals. PLOS ONE 04 Ağustos. 2025;20(8):e0327872. 10.1371/journal.pone.0327872.
52. Lanza-León P, Cantarero-Prieto D, Pascual-Sáez M. Exploring trends and determinants of basic childhood vaccination coverage: Empirical evidence over 41 years. PLOS ONE 21 Mart. 2024;19(3):e0300404. 10.1371/journal.pone.0300404.
53. Adetokunboh O, Iwu-Jaja CJ, Nnaji CA, Ndwandwe D. Missed opportunities for vaccination in Africa. Curr Opin Immunol. 01 Ağustos 2021;Vaccines * SS on Widening perspectives on the BAFF family Ligands & receptors71:55–61. 10.1016/j.coi.2021.05.002
54. Adamu AA, Uthman OA, Gadanya MA, Adetokunboh OO, Wiysonge CS. A multilevel analysis of the determinants of missed opportunities for vaccination among children attending primary healthcare facilities in Kano, Nigeria: Findings from the pre-implementation phase of a collaborative quality improvement programme. PLoS ONE. 2019;14(7):e0218572. 10.1371/journal.pone.0218572 . PubMed PMID: 31291267; PubMed Central PMCID: PMC6619653.
55. Page B, Irving D, Amalberti R, Vincent C. Health services under pressure: a scoping review and development of a taxonomy of adaptive strategies. BMJ Qual Saf 01 Kasım. 2024;33(11):738–47. 10.1136/bmjqs-2023-016686 . PubMed PMID: 38050158.
56. Sabety AH, Jena AB, Barnett ML. Changes in Health Care Use and Outcomes After Turnover in Primary Care. JAMA Intern Med. 01 Şubat. 2021;181(2):186 – 94. 10.1001/jamainternmed.2020.6288
57. Reddy A, Pollack CE, Asch DA, Canamucio A, Werner RM. The Effect of Primary Care Provider Turnover on Patient Experience of Care and Ambulatory Quality of Care. JAMA Intern Med 01 Temmuz. 2015;175(7):1157–62. 10.1001/jamainternmed.2015.1853.
58. DeSilva MB, Haapala J, Vazquez-Benitez G, Daley MF, Nordin JD, Klein NP. vd. Association of the COVID-19 Pandemic With Routine Childhood Vaccination Rates and Proportion Up to Date With Vaccinations Across 8 US Health Systems in the Vaccine Safety Datalink. JAMA Pediatr 01 Ocak. 2022;176(1):68–77. 10.1001/jamapediatrics.2021.4251.
59. Mekonnen ZA, Gelaye KA, Were MC, Tilahun B. Timely completion of vaccination and its determinants among children in northwest, Ethiopia: a multilevel analysis. BMC Public Health 11 Haziran. 2020;20(1):908. 10.1186/s12889-020-08935-8.
60. Khan J, Shil A, Mohanty SK. Hepatitis B vaccination coverage across India: exploring the spatial heterogeneity and contextual determinants. BMC Public Health 12 Eylül. 2019;19(1):1263. 10.1186/s12889-019-7534-2.
61. Cunha NSP, Fahrat SCL, de Olinda RA, Braga ALF, Barbieri CLA, de Aguiar Pontes Pamplona Y. vd. Spatial analysis of vaccine coverage on the first year of life in the northeast of Brazil. BMC Public Health 16 Haziran. 2022;22(1):1204. 10.1186/s12889-022-13589-9.

62. Choudhary TS, Reddy NS, Apte A, Sinha B, Roy S, Nair NP. vd. Delayed vaccination and its predictors among children under 2 years in India: Insights from the national family health survey–4. Vaccine 17 Nisan. 2019;37(17):2331–9. 10.1016/j.vaccine.2019.03.039.
63. Ngo-Bebe D, Mechael P, Kwilu FN, Bukele TK, Langwana F, Lobukulu GL. vd. Assessing the use of geospatial data for immunization program implementation and associated effects on coverage and equity in the Democratic Republic of Congo. BMC Public Health 24 Ocak. 2025;25(1):311. 10.1186/s12889-025-21578-x.
64. Ali D, Levin A, Abdulkarim M, Tijjani U, Ahmed B, Namalam F. vd. A cost-effectiveness analysis of traditional and geographic information system-supported microplanning approaches for routine immunization program management in northern Nigeria. Vaccine 05 Şubat. 2020;38(6):1408–15. 10.1016/j.vaccine.2019.12.002.
65. Olstad DL, McIntyre L. Reconceptualising precision public health. BMJ Open 01 Eylül. 2019;9(9):e030279. 10.1136/bmjopen-2019-030279 . PubMed PMID: 31519678.

Figures

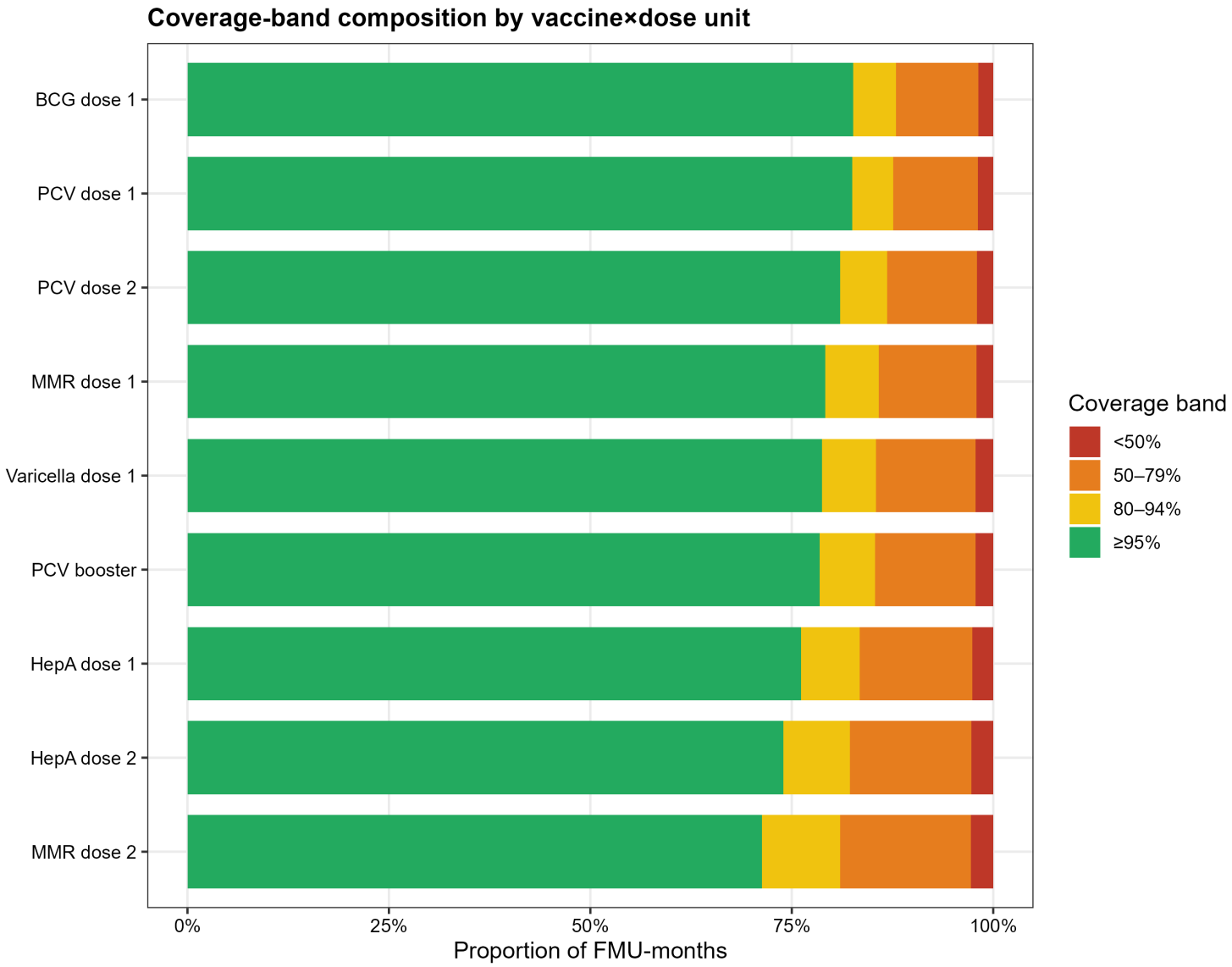


Figure 1

Coverage-band composition by vaccine-dose unit (proportion of FMU-months). Bands: ≤50%, 50-79%, 80-94% and ≥95%.

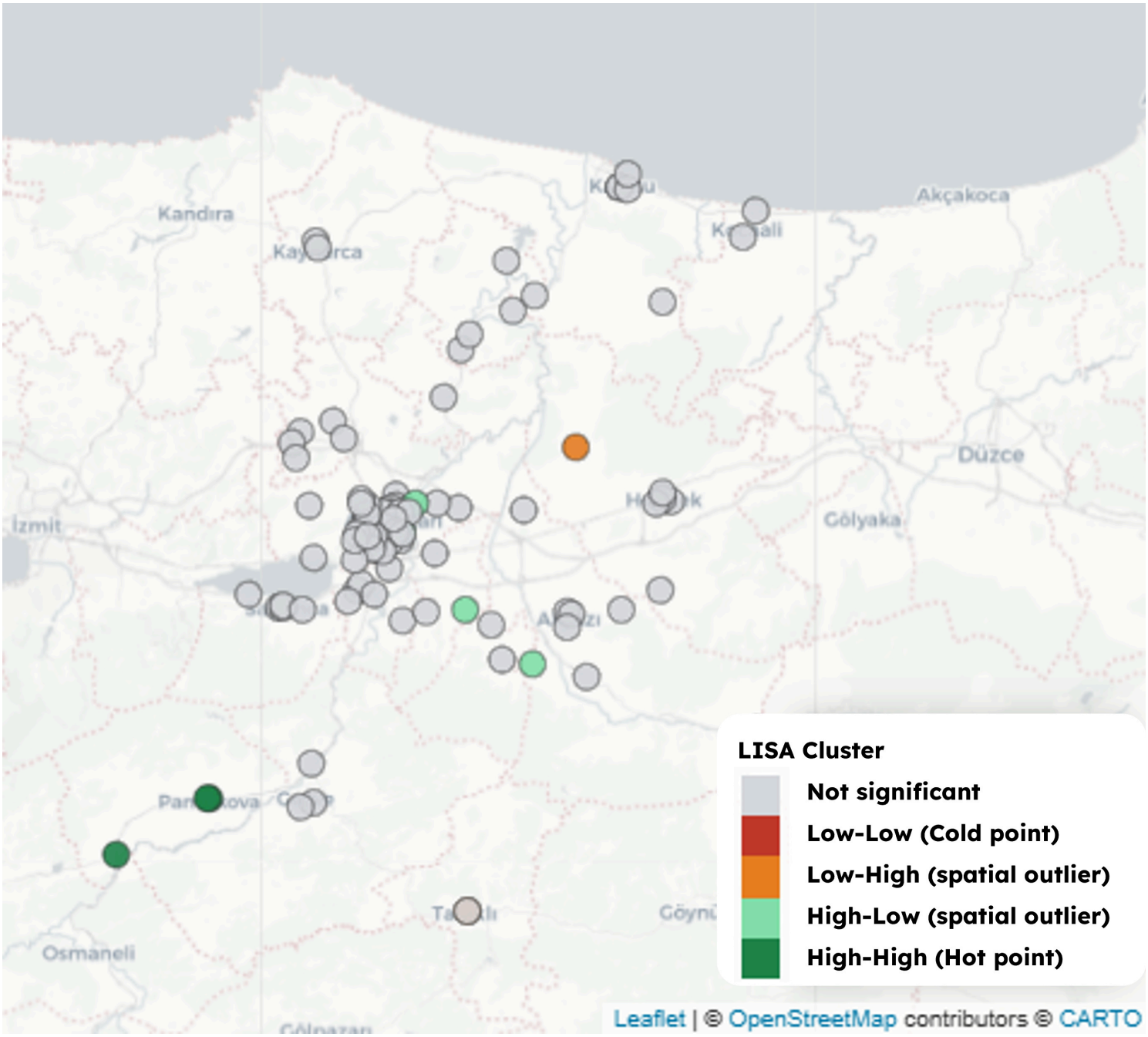


Figure 2

Local Moran (LISA) clusters for HepA dose 2 (k = 3). Green: high-high (hot spot); no significant low-low (cold spot) cluster was detected at k = 3.

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