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COLLEGE OF HEALTH SCIENCES, SCHOOL OF PHARMACY

PHD PROGRAM IN SOCIAL AND ADMINISTRATIVE PHARMACY

VACCINATION DROPOUT, SOCIOECONOMIC INEQUALITY AND SPATIAL DISTRIBUTION OF VACCINATION DROPOUT AND ZERO-DOSE CHILDREN AGED 12-35 MONTHS IN REMOTE AND UNDERSERVED SETTINGS OF ETHIOPIA

A PhD Dissertation submitted to the Department of Pharmaceutics and Social Pharmacy, School of Pharmacy, College of Health Sciences

Presented in partial fulfillment for the Degree of Doctor of Philosophy in Social and Administrative Pharmacy

By: Fisseha Shiferie (B.Pharm, M.Pharm, MPH)

Supervisor:

Prof. Teferi Gedif Fenta (B.Pharm, MPH, PhD)

Co-supervisors:

Samson Gebremedhin (MPH, PhD)

Prof. Gashaw Andargie (MPH, PhD)

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This is to certify that the thesis prepared by Fisseha Shiferie Tadesse, entitled *Vaccination dropout, socioeconomic inequality and spatial distribution of vaccination dropout and zero-dose children aged 12-35 months in remote and underserved settings of Ethiopia* and submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy (PhD) in Social and Administrative Pharmacy complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the Examining Committee:

		Name	Signature	Date
1.	Advisor:	Prof. Teferi Gedif Fenta	Teferi G.	10th Oct 2024
2.	Advisor:	Dr. Samson G/Medhin		Oct 11, 2024
3.	Advisor:	Prof. Gashaw Andargie		Oct 10, 2024
4.	Internal Examiner:	Dr. Bruck Messele		October 8, 2024
5.	External Examiner:	Prof. Karl Blanchet		October 8, 2024

Chair of the Department:

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LIST OF ORIGINAL PAPERS

This thesis is prepared based on the following four articles which are listed below and annexed as paper I, paper II, paper III and paper IV at the end of the thesis.

I. Vaccination dropout and wealth related inequality among children aged 12–35 months in remote and underserved settings of Ethiopia: a cross-sectional evaluation survey
II. Decomposition analysis of socioeconomic inequalities in vaccination dropout in remote and underserved settings of Ethiopia
III. Low Measles Vaccination Coverage and Spatial Analysis of High Measles Vaccination Dropout in Ethiopia's Underprivileged Areas
IV. Spatial distribution of zero-dose children in Ethiopia: evidence for a targeted intervention from a large-scale cross-sectional evaluation survey

ABSTRACT

Vaccination is considered as one of the most successful and cost-effective public health measures, averting millions of deaths every year. Although vaccination coverage is increasing globally, many children in low- and middle-income countries drop out of the vaccination continuum. Globally, 25 million children were either underimmunized or zero-dose in 2021. Inequality in access to childhood vaccinations is also another major obstacle to the astounding progress in basic vaccination coverage. This study was conducted to estimate the prevalence of vaccination dropout, examine socioeconomic inequalities in vaccination dropout, decompose socioeconomic inequalities and map the spatial distribution of zero-dose and measles vaccination dropout children in underserved settings of Ethiopia. A generalized estimating equation was used to assess determinants of vaccination dropout and concentration curve and index were used to estimate wealth related inequality of vaccination dropout. A decomposition analysis approach was used to decompose socioeconomic inequalities into the contributions of individual factors to inequalities in vaccination dropout. Spatial autocorrelation was measured using the Global Moran's I statistic. Getis-Ord Gi* statistics was applied to calculate the spatial variability of zero-dose and measles vaccination dropout cases. Spatial interpolation technique was also applied to predict unknown values that fall between known values. A total of 3,646 mothers/caregivers of children participated in the study. The overall Penta-1 to Penta-3 dropout estimate was 44%. Developing regions and urban slums had the highest and the lowest vaccination dropout estimates (60.1% and 11.2%), respectively. Caregivers who were working outside their homes, who did not receive a service from a skilled birth attendant, who were less gender empowered and who were in the lowest wealth strata had increased odds of Penta-1 to Penta-3 dropout. Inequalities in vaccination dropout were significantly and disproportionately concentrated among the poor (CI = −0.179; $p < 0.01$). According to the decomposition analysis, wealth index, place of residence, skilled birth attendance, and availability of a health facility in the kebele contributed the most to socioeconomic inequalities in vaccination dropout. Overall, MCV-1 and MCV-2 coverages were 67% and

35%, respectively. On average, the measles vaccination dropout estimate was 48.3%. Refugees and urban slums had the highest and the lowest measles vaccination dropout estimates (56.4% and 37.7%), respectively.

The hot spot analysis detected the highest burden of measles vaccination dropout in the Afar Region's zones 1 and 5, the Amhara Region's North Gondar Zone and the Somali Region's Siti Zone. Western, eastern and northern parts of Somali and western and central parts of Afar regions had the highest load of zero-dose children. Vaccination dropout estimates were high among children residing in remote, hard-to-reach, and conflict-affected settings of Ethiopia. The overall MCV-1 and MCV-2 coverage estimates were low, measles vaccination dropout was high. The highest burdens of zero-dose and measles vaccination dropout cases were detected mainly in the northeastern parts of Ethiopia.

Strengthening horizonal integration of immunization services with maternal & child health services and empowering women would help reduce vaccination dropout. Due to its recent introduction, the lack of awareness around MCV-2 needs to be addressed, especially in the northeastern part of Ethiopia.

ABBREVIATIONS AND ACRONYMS

ANC	Antenatal Care
OPV3	Oral polio vaccine third-dose
PNC	Postnatal Care
EPI	Expanded Programme for Immunization
AOR	Adjusted Odds Ratio
COR	Crude Odds Ratio
BCG	Bacillus Calmette–Guérin
MCV-1	Measles-Containing-Vaccine First-Dose
MCV-2	Measles-Containing-Vaccine Second-Dose
CSA	Central Statistical Agency
EDHS	Ethiopian Demographic and Health Survey
EA	Enumeration Area
SBA	Skilled Birth Attendance
CnI	Concentration Index
CC	Concentration Curve
IDPs	Internally Displaced Populations
SNNP	Southern Nations, Nationalities, and Peoples
VIF	Variance Inflation Factor
AFR	African Region
DTP1	Diphtheria–Tetanus–Pertussis-Containing-Vaccine First-Dose
DTP3	Diphtheria–Tetanus–Pertussis-Containing-Vaccine Third-Dose
Penta-1	Pentavalent-1
Penta-3	Pentavalent-3

WHO	World Health Organization
GPS	Global Positioning System
SDG	Sustainable Development Goal
IA2030	Immunization Agenda 2030
COVID-19	Coronavirus disease
DRC	Democratic Republic of the Congo
CSDH	Commission on Social Determinants of Health
GVAP	Global Vaccine Action Plan
WHA	World Health Assembly

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CHAPTER I: INTRODUCTION

1.1. Background of the study

Vaccination is regarded as one of the most successful and economical public health measures, averting millions of deaths every year. Despite the fact that vaccination coverage is increasing globally, many children in low- and middle-income countries drop out of the vaccination continuum (Chanie et al., 2021, Elsland et al., 2021, Kayembe-Ntumba et al., 2022). The global coverage of immunization dropped from 86% in 2019 to 81% in 2021 (WHO, 2021a).

Globally, 25 million children were either underimmunized (those who missed the third dose of the diphtheria-tetanus-pertussis-containing vaccine, DTP3) or zero-dose (those who missed the first dose of diphtheria-tetanus-pertussis-containing vaccine, DTP1) in 2021 (UNICEF, 2021). In 2019, 19.7 million children did not receive the DTP3 vaccination in their first year of life that is a crucial sign of the effectiveness of immunization programs. Every year, 4.4 million children in sub-Saharan Africa die from communicable diseases that could be prevented by vaccination (Gebeyehu et al., 2022).

Gavi (The Vaccine Alliance), which was founded in 2000 to increase immunization access in lower-income countries, assists in immunizing nearly half of all children worldwide (Gavi, 2021a). In 2012, the World Health Assembly (WHA) unanimously approved the Global Vaccine Action Plan 2011–2020 (GVAP). The goal of GVAP was to bring the Decade of Vaccines vision of a world free from vaccine-preventable diseases to all people and communities (WHO, 2013, Hwang et al., 2020). Even though the introduction of new vaccines and vaccine research and development have advanced significantly, four of the five GVAP goals were not achieved by the end of the decade: reaching vaccine coverage and equity targets; eradicating polio; and eliminating measles, rubella, congenital rubella syndrome, and maternal and neonatal tetanus continues to be difficult problems (Hwang et al., 2020).

Reaching zero-dose children is receiving more attention globally in an effort to decrease vaccine inequality. Gavi's 5.0 strategy aims to close the Sustainable Development Goals (SDGs) by reducing the number of zero-dose children by 25% by 2025 and by 50% by 2030 (Gavi, 2021a, Gavi, 2024). Furthermore, the WHA has approved the Immunization Agenda 2030 (IA2030), a new worldwide vision and strategy, with the assistance of nations and partners. In order to improve health and well-being, IA2030 envisages a world in which everyone, everywhere, at every age, fully benefits from vaccinations. It seeks to preserve hard-fought advancements in immunization, bounce back from Coronavirus disease (COVID-19) disruptions, and accomplish even more by ensuring that no one is left behind at any stage of life (WHO, 2020).

To date, Ethiopia has made encouraging gains in immunization coverage. According to the Ethiopian Mini-Demographic and Health Survey (Mini-EDHS) 2019, the coverage of complete vaccination among children 12-35 months increased from 20% in 2000 to 44% in 2019 (EPHI and ICF, 2019) (Figure 1). The Expanded Programme for Immunization (EPI) of Ethiopia is currently administering 12 different antigens to infants born in the country each year. The vaccination service is mainly provided at health centers and health posts through a mix of static, outreach, and mobile activities. Polio, measles, and meningitis vaccines are also being administered by large-scale periodic campaigns (MOH-Ethiopia, 2021).

A study using data from the EDHS 2019 revealed a significant association between childhood vaccination and mothers' educational attainment, marital status, possession of a vaccination record, and place of residence. Children born to mothers who did not attend school had lower levels of partial or complete vaccinations than children whose mothers did not attend school (Wondimu A et al., 2020, Sako S et al., 2023). Children with married mothers were more likely to have received all recommended vaccinations. Maintaining vaccination cards was also linked to receiving all recommended vaccinations. The likelihood of full vaccination was lower in children born to mothers from semi-pastoralist areas like Gambella, Benishangul-Gumuz, and Harari, as well as pastoralist regions like Afar and Somali. The study also indicated that compared to children living in urban areas, children in rural areas of Ethiopia had lower rates of full vaccination (Sako S et al., 2023, Lakew Y et al., 2015). Vaccination coverage was higher for children born to mothers in the rich wealth index group than for children born to mothers in the poor wealth index group (Lakew Y et al., 2015). Furthermore, a study indicated that higher immunization coverage was associated with institutional delivery, a shorter walking distance to the closest health facility, antenatal care visits, living in an urban area, having a healthcare provider visit your home, and being well-informed about the immunization schedule (Zemariam AB et al., 2024).

A study done in pastoral and semi-pastoral regions in Ethiopia showed that among children who had received at least one vaccine, 20.5% failed to take at least one of the next higher doses. The dropout rate between pentavalent 1 and measles vaccinations was 14.1% followed by Bacille Calmette-Guerin (BCG) and measles (10.1%), both of which are higher than 10%, the maximum tolerable dropout rate by the World Health Organization (WHO) (Tessema et al., 2019).

Vaccination dropout refers to the proportion of children who did not get the subsequent vaccine among those who received the first vaccine. It is determined by calculating the proportion of children who dropped out from the immunization system between penta-1 and penta-3 or penta-1 and measles-containing-vaccine first-dose (MCV-1), BCG and MCV-1, BCG and measles-containing-vaccine second-dose (MCV-2), BCG and penta-1, BCG and penta-3 or MCV-1 and MCV-2 (Wariri et al., 2019, Baguune et al., 2017). Dropout rates are used to measure program continuity of children in immunization. According to the WHO, a dropout rate of >10% is considered to be undesirable and shows that a health facility has utilization constraints. In contrast, a low dropout rate is indicative of good utilization and therefore of good service quality (Mmanga et al., 2022, Powelson et al., 2022, Hailu et al., 2022).

Inequalities in access to childhood vaccination remain the other outstanding challenge to the remarkable advancement in basic vaccination coverage. Data on inequalities in child vaccination showed that richer subgroups tend to have higher coverage whereas the coverage among poorer subgroups varied across countries (Arsenault et al., 2017). For example, studies in India, Nigeria and Brazil indicated that children of mothers who had higher education levels and household wealth status are more likely receive higher vaccination coverage (Shrivastwa et al., 2015, Ataguba et al., 2016, Branco et al., 2014).

According to the EDHS 2011 and 2016, the uptake of BCG, DTP3, Oral Polio Vaccine-3 (OPV3) and measles were disproportionately concentrated among children from wealthy households. The results of the decomposition analysis showed that the significant contributors to socioeconomic inequality in basic vaccination status included; wealth index, maternal education, contraceptive use, antenatal care (ANC) contacts, exposure to media and place of residence. The use of maternal health services had the highest significant contributions to socioeconomic inequalities in child vaccination. ANC contacts had 45.4% contribution in 2011 and 50.4% in 2016. Wealth index is the other significant contributor, 23.9% in 2011 and 21.2% in 2016. On the other hand, rural residence had a negative contribution to socioeconomic inequalities in child vaccination on both surveys (Bobo and Hayen, 2020, CSA and ICF, 2012, CSA and ICF, 2016). Despite the establishment of increasing number of service delivery points closer to the community in the last two decades and vaccination services are provided free of service charges at the public health facilities, substantial inequality due to wealth index had persisted in Ethiopia (Yibeltal et al., 2022, Geweniger and Abbas, 2020, Hosseinpoor et al., 2016). Another study conducted by Wondimu et al indicated the presence of persistent socioeconomic inequalities in terms of vaccine uptake. Children from the poorest households lagged behind those from relatively wealthy households in vaccination. The decomposition analysis of socioeconomic inequalities revealed that maternal educational level, ANC contacts, institutional delivery, and exposure to media consistently contributed to the inequality observed in vaccine uptake (Wondimu et al., 2021).

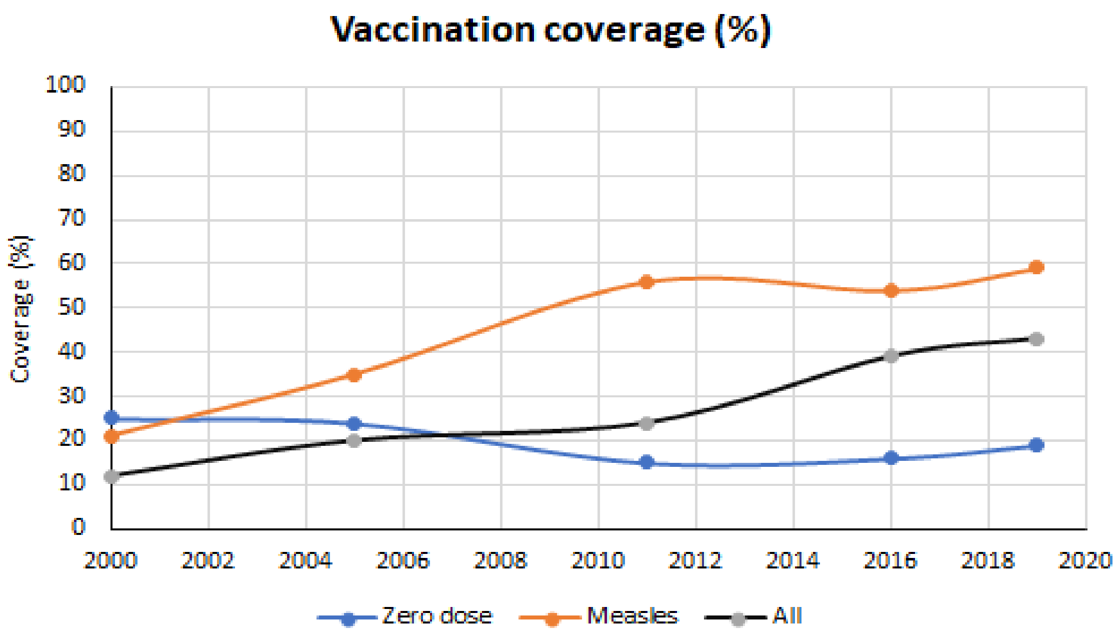

Figure 1: Trends in vaccination coverage in Ethiopia (based on national DHS surveys)

1.2. Statement of the problem

Gavi's 5.0 Strategy is guided by a "missed communities, first priority" principle to prioritize children missing vaccinations, particularly those found in displaced and vulnerable communities. Almost half of these missed children reside in fragile and conflict-affected settings. Studies focused on immunization, including zero-dose and dropout children, have not been extensively conducted in underserved settings including pastoralist regions, developing regions, newly-established regions, conflict-affected areas, underserved urban populations, internally displaced populations (IDPs), and refugee populations, especially after the two great challenges (COVID-19 and domestic violence) Ethiopia has recently experienced. In addition, detecting spatial heterogeneity of childhood vaccination to identify gaps in the performance of immunization programs so as to target low-coverage population clusters can help to accelerate disease elimination. However, as far as our knowledge goes, there is no study that depicted the spatial distribution of zero-dose and measles vaccination dropout children in Ethiopia. Hence, this study was conducted to estimate the prevalence of vaccination dropout and identify factors, examine socioeconomic inequalities in vaccination dropout, decompose socioeconomic inequalities into the contributions of individual factors and map the spatial distribution of high and low risk areas for zero-dose and measles vaccination dropout children aged 12-35 months in remote and underserved settings of Ethiopia.

1.3. Significance of the study

Ethiopia has made substantial gains in increasing coverage of childhood vaccination. Between 2000 and 2019, proportion of children who received all the routine antigens increased from 15 to 44%, and that of MCV-1 doubled from 32 to 59%. Proportions of zero-dose and under-immunized have been also reduced by 32 and 40 percentage points, respectively. Yet, important challenges remain unaddressed. In 2019, 23% of children 12-23 months of age were zero-dose and 39% under-immunized. Among GAVI-supported countries, Ethiopia is ranked fourth based on burden of zero-dose immunization. Other outstanding challenges include high vaccination dropout, and geographic and socio-economic inequality. The recent political unrest and COVID-19 pandemic have also threatened to revert the hard-fought gains. Ethiopia is now giving focus to end this inequity, making reaching zero-dose, under immunized and dropout children with immunisation as a key priority for the next few years.

The findings of this study will be used as inputs to inform immunization program planning and implementation targeting zero-dose, dropout, underimmunized children and vaccination inequality in 2023 and beyond. More importantly, the research will answer critical questions that will ultimately help reduce the high burden of zero-dose and dropout children and inequalities in access to childhood vaccination which is in line with IA2030 and GAVI 5.0 strategy.

Findings of the study will also play significant roles in the national efforts of improving immunization coverage in hard to reach and underserved settings in Ethiopia. The findings are also expected to highlight potential strategies and policy recommendations to address the gaps related to zero dose, dropout and socioeconomic inequalities in remote and underserved settings of Ethiopia.

CHAPTER II: LITERATURE REVIEW

2.1. Vaccination dropout and its determinants

The EPI was established by the WHO in 1974 to guarantee that all children receive the four vaccines that are regularly recommended (BCG, polio, MCV, and DTP), which provide protection against six diseases (Uwizihiwe & Bock, 2015). Since its establishment, vaccines have significantly decreased morbidity, disability, and mortality globally among under-five children, thereby reducing vaccine-preventable diseases (Andre et al., 2008, Philippe et al., 2009). The WHA approved the GVAP in 2012 and mandates that by 2020, every nation must achieve a minimum of 90% national coverage for all vaccines included in the routine immunization schedule (WHO, 2013). Nevertheless, in many regions of the world, children were still lacking some vaccinations against diseases targeted by EPI. Seventy-one countries (37%) and sixty-four (33%) still haven't achieved the 2012–2020 Global Measles and Rubella Strategic Plan target of ≥90% national MCV1 coverage and ≥90% national DTP3 coverage, respectively (Feldstein et al., 2017, WHO, 2012).

Vaccine-preventable diseases pose a public health concern in developing countries where it is thought to be the cause of 10 million deaths of under-five children each year (WHO, 2021a). Over 2.5 million child deaths worldwide can be averted with a successful immunization program which is the most cost-effective public health intervention globally (WHO, 2009).

There has been some improvement in the global vaccination coverage in 2022. Yet, 20.5 million children worldwide—2.1 million more than in 2019—do not have access to life-saving vaccinations. Global coverage of the DTP3 vaccine, which is frequently used to evaluate how well countries are doing in providing children with routine immunization services, decreased. Its coverage in 2019 was 86%, but it had fallen to 81% by 2021, which was the lowest since 2008. All regions demonstrated varied degrees of recovery in 2022 compared to 2021 with the exception of sub-Saharan Africa (UNICEF, 2021) where infectious diseases that could be prevented through vaccination claim the lives of 4.4 million children annually (Gebeyehu et al., 2022).

Sub-Saharan Africa is also well-known for having a high rate of vaccination dropouts, with Nigeria having the highest rate (33.6%) and Ghana having the lowest (11.13%). Research done in the community (39%) showed a higher vaccination dropout rate than research done in institutions (13.7%). This could be as a result of the fact that women residing in institutions have adequate access to health information (Gebeyehu et al., 2022). According to a study, living in a rural area, having a mother without a regular job, and traveling long distances to health facilities are some of the factors linked to vaccination dropout (Thapa et al., 2021).

In an effort to lower morbidity and mortality from vaccine preventable diseases, Ethiopia adopted the EPI in 1980. To increase vaccination coverage, two strategies were introduced in 2003: Reaching Every District and Sustainable Outreach Services (MOH-Ethiopia, 2015). By 2020, the GVAP and the EPI planned to have 90% nationwide coverage and 80% district-level coverage (Geweniger and Abbas, 2020).

As per Ethiopia's standard immunization schedule, newborns should start receiving vaccinations at birth and complete them before turning one year old. This includes getting the first dose of the oral polio vaccine and a single dose of the BCG vaccine at birth or as soon as possible. OPV-3, Pentavalent, Rota1, Rota 2, and pneumonia conjugate vaccines are given at the 6th, 10th, and 14th weeks and the MCV-1 and MCV-2 vaccines are given at the age of 9 and 15 months, respectively (Kasahun et al., 2015, MoH-Ethiopia, 2021, Okwaraji et al., 2012).

According to 2019 Mini-EDHS data, only 61% of children received all three recommended doses of DTP, compared to 76% of children who received DTP1. The percentage of children aged 12–23 months who received DTP1 was 72.7%, while only 50.8% received DTP3 (EPHI and ICF, 2019).

According to a research done in underprivileged areas of Ethiopia, 20.5% of children who received at least one vaccination did not receive at least one dose of the subsequent shots. This study showed that the dropout rate between pentavalent 1 and MCV-1 was 14.1% and followed by BCG and MCV-1 was (10.1%). Both of these dropout rates are higher than the WHO maximum allowable dropout rate of 10% (Tessema et al., 2019). Additionally, a very recent study revealed that the dropout rate of pneumonia conjugate vaccine among children aged 12–23 months in Ethiopia was 20.2% (Assefa et al., 2024). As per the Ethiopian Health Sector Transformation Plan II 2020/2021–2024/2025, the national vaccination dropout rate, using pentavalent 1 and measles antigens, was 13%, and approximately 19% of children had no vaccinations at all (MoH-Ethiopia, 2021a).

Research showed that incomplete vaccination was significantly associated with mother's age, place of delivery, family size, marital status, residence, income, and level of education (Zenbaba et al., 2021, Abebe et al., 2019). Additionally, it was discovered that living in emerging regions and having a vaccination card were linked to vaccination dropout. The PCV dropout rate is lower in children whose mothers have vaccination cards than in those whose mothers do not. Children of respondents living in emerging regions had greater odds of vaccination dropout than respondents living in city administrations. This could be as a result of the majority of respondents from emerging regions are from remote and hard-to-reach areas.. Mothers in these communities are also less conscious of the benefits of getting health care and immunizing their children. Another possible reason for the increased awareness of childhood vaccination among respondents residing in city administrations could be their increased access to media channels such as newspapers, radio, and television (Assefa et al., 2024).

2.2. Decomposition analysis of socioeconomic inequalities in vaccination dropout

SDG-10 called for reducing inequality both within and between nations (UN, 2015). The effectiveness of immunization programs in increasing vaccination coverage and equitable uptake was linked to 14 of the 17 SDGs (Gavi, 2019).

One of the six guiding principles and strategic objectives of the GVAP 2011–2020 was equitable access to immunizations. It promotes the monitoring of equity indicators, such as the difference in vaccination coverage between the wealthiest and lowest quintiles (WHO, 2013). Through public-private partnerships, Gavi has improved immunization access in the world's poorest countries. Its 2016–2020 vaccine goal indicators also included measures of vaccine equity related to wealth, maternal education, and geographic distribution (Gavi, 2019a). The EPI is in line with the SDGs 2016–2030, the GVAP 2011–2020, and Gavi in setting equity goals for health outcomes and vaccination coverage (Geweniger and Abbas, 2020).

There have been pro-urban, pro-rich, and pro-educated disparities in vaccination coverage in sub-Saharan African nations despite the consistent increases in immunization coverage over the previous few decades (Bangura et al., 2020, Wiysonge et al., 2012, Restrepo-Mendez et al., 2016). The largest disparities in immunization coverage and dropout rates were found in West African nations like Guinea, Mali, and Nigeria. These differences were primarily caused by poverty, low maternal education, and residence in certain underprivileged subnational areas. There were more than 20 percentage points of difference in BCG and DTP3 coverage and dropout rates between the richest and poorest, high- and low-coverage regions, and children of mothers with at least a secondary education and those without any formal education in these countries. According to this study, the disparity in coverage and dropout rates was only slightly influenced by the resident's location (Wariri et al., 2019). A study done across 24 African nations indicated that there was at least a 14.9% variation in vaccination dropout estimates between the highest and lowest quintiles. These disparities in the dropout rate were caused by lower estimated national vaccination rates (Kirkby et al., 2021).

In Ethiopia, there are no out-of-pocket costs associated with receiving vaccinations because these services are offered at public health facilities at no cost. Initiatives were also undertaken to utilize health extension workers to reach the impoverished and rural populations. However, studies still continued to demonstrate that vaccination coverage inequality was related to household wealth status (Ambel et al., 2017, MOH-Ethiopia, 2015, WHO, 2016c). This could be the result of non-financial barriers that prevent lower socioeconomic households from accepting vaccines, in addition to additional financial barriers beyond out-of-pocket expenses like transportation costs and productivity loss from taking time off to access vaccination services (Geweniger and Abbas, 2020).

Studies revealed that the poorest quintile had the lowest estimates of full vaccination coverage. With respect to geographic characteristics, children living in urban areas had higher full vaccination coverage than those in rural areas. Addis Ababa had the highest reported vaccination coverage, while the Afar region had the lowest. Children whose mothers were between 35 and 49 years old at the time of birth, who were not married and who lived in households headed by women had the lowest vaccination coverage (Geweniger and Abbas, 2020, Tamirat et al., 2019, Kinfe et al., 2019). A Thorpe et al study demonstrated a positive association between increased vaccination coverage and women's empowerment (Thorpe et al., 2016).

According to data from the EDHS 2011 and 2016, children from richer households were more likely to receive the BCG, DTP3, OPV3, and measles vaccinations. The results of a decomposition analysis revealed that the wealth index, maternal education, contraceptive use, ANC contacts, media exposure, and place of residence were the main factors contributing to socioeconomic inequality in basic vaccination status (Bobo and Hayen, 2020, CSA & ICF 2012, CSA & ICF 2016).

2.3. Spatial analysis of zero-dose children

In recent years, the global health community has focused more on precisely identifying and targeting populations at risk of vaccine-preventable diseases based on their geographic location. This makes it easier to pinpoint underprivileged communities and allows for more targeted interventions and resource distribution (Utazi et al., 2023, Utazi et al., 2019).

Estimates for the number of zero-dose children in 2020 were 12.4 million, with the majority residing in sub-Saharan Africa or conflict-affected regions (Gavi, 2024, Utazi et al., 2023). Investigations conducted prior to the Covid-19 pandemic showed that zero-dose children accounted for almost half of all vaccine-preventable deaths (Taneja et al., 2023).

The Gavi 2021 estimate stated that three important geographic contexts—urban areas, remote communities, and populations in conflict settings—were home to approximately 50% of zero-dose children. Even though the Gavi operates in most of the countries where these missed communities were present, two-thirds of zero-dose children in 2019 resided in just five nations: Nigeria, India, the Democratic Republic of the Congo (DRC), Pakistan, and Ethiopia. There exist notable disparities both among and between countries. For instance, the DRC and Ethiopia had the highest proportion of zero-dose children residing in remote rural areas, whereas Nigeria had the highest number of zero-dose children in conflict affected areas (Gavi, 2021).

Although there have been notable advancements in the number of infant vaccinations, Ethiopia ranked fourth globally in terms of the number of zero-dose children, with 1.1 million (WHO/UNICEF, 2021). A study by Biks et al indicated that the prevalence of zero-dose children in underserved settings of Ethiopia was 33.7%. Developing and pastoralist regions, internally displaced peoples, newly formed regions, and conflict-affected areas had the highest prevalence of zero-dose children (Biks et al., 2024). The high proportion of zero-dose children in these settings was associated with supply-side barriers such as inadequate information being provided by health workers, irregularities in service provision, suboptimal staff motivation, high staff turnover, closure and inaccessibility of health facilities, lack of functional health posts, service provision limited to selected days or hours, and gender norms viewing females as responsible for childcare. Demand-side barriers included religious beliefs, cultural norms, fear of vaccine side effects, and lack of awareness and sustained interventions (Biks et al., 2024a).

In Ethiopia, the spatial distribution of DTP-containing vaccine alone has never been mapped. Nevertheless, research revealed significant regional variation in the vaccination coverage for other vaccines. These studies showed that the Somali, Afar, Northwest Gambella, Western and Eastern parts of Southern Nations, Nationalities, and Peoples (SNNP), and Oromia regions had the lowest proportion of childhood immunization, while Addis Ababa and the Amhara region had the highest proportion (Nour et al., 2020a, Nour et al., 2020b, Tesfa et al., 2023, Melaku et al., 2020, Mosser et al., 2019). Southwest Afar, East and Northwest Somali were at risk of Bacillus Calmette–Guérin (BCG) vaccination coverage (Agegnehu et al., 2021). This could be due to the fact that these areas are borderlands and cannot thus access or use healthcare services. One possible explanation for the low percentage of childhood vaccinations in these areas could be the lower educational attainment of the local population (Abebe et al., 2019). On the other hand, northern, western, and central Ethiopia were found to have high BCG vaccination coverage (Atalell et al., 2022a).

2.4. Measles vaccination coverage and spatial analysis of measles vaccination dropout

Measles is still a leading cause of disease and mortality globally, particularly in the WHO African Region (AFR) (Minta et al., 2022). AFR's low vaccination coverage has been primarily caused by the low coverage of MCV1 in populous countries like Ethiopia, Nigeria, and the DRC (WHO, 2017, Venkatesan et al., 2022).

Measles is endemic in Ethiopia with annual reports of cases. In 2021, the coverages of MCV1 and MCV2 were 54% and 46%, respectively (WHO, 2023). Ethiopia has developed a measles eradication plan with the aim of accomplishing it by 2020. Nevertheless, the MCV-1 coverage in the country was 59%, with the Afar region having the lowest coverage (28.5%), according to the Mini-EDHS 2019 report (Masresha et al., 2023). A study that used the Mini-EDHS 2019 data indicated that the coverage of MCV2 was 12.36% (Muluneh et al., 2022). An MCV2 coverage of 42.5% was estimated by a 2022 study carried out in urban areas of the North Showa Zone in central Ethiopia. The study indicated that lack of knowledge about the necessity of returning for a second dose of the measles vaccination was the main cause for not taking the MCV2 (Tadesse et al., 2022).

MCV2 should follow MCV1 through routine service strategies, according to WHO and UNICEF, as this is essential to guaranteeing full immunization. However, mainly due to maternal education, healthcare access, and poverty, MCV2 uptake falls short of targets, particularly in Sub-Saharan Africa (Chilot et al., 2022, Plans-Rubió, 2019, WHO, 2017). The measles vaccination dropout estimate, which represents the proportion of children who miss the vital second dose, is a key measure of the effectiveness of an immunization program (WHO, 2020a). According to a study by Zegeye et al, 33.26% of under-five children in Ethiopia dropped out from the measles vaccination (Zegeye et al., 2024).

Low childhood MCV-1 vaccination coverage was found in Ethiopia's Somali, Afar, Gambella, and Oromia regions (Geremew et al., 2019). The likelihood of receiving MCV1 vaccination was found to be positively associated with child age, the first and third doses of pentavalent vaccination, secondary and above maternal education, and media exposure. Conversely, the likelihood of receiving MCV1 vaccination was negatively linked with older maternal age (Geweniger and Abbas, 2020).

A hot spot analysis detected geographic variations in measles vaccination dropout in the northwest, northern, central, and eastern regions of Ethiopia. The most likely reason for this geographic variation in measles vaccination dropout rates could be attributed to notable variations in infrastructure, including the distribution of healthcare professionals and facilities among regions, as well as variations in roads, electricity, and water (Geremew et al., 2019, Hailu et al., 2022). Moreover, there are regional differences in the distribution of vaccines, cultural differences, sociodemographic characteristics of mothers, and societal attitudes and vaccination awareness (Assefa et al., 2016, Woldemichael et al., 2019).

2.5. Conceptual model

The conceptual model for this study was adopted from the WHO Commission on Social Determinants of Health (CSDH) (Figure 2). The CSDH conceptual framework model illustrates the way social, economic, and political systems lead to a range of socioeconomic statuses, resulting in the stratification of populations based on income, education, occupation, gender, race/ethnicity, and other factors. The social positions of individuals influence the factors that determine their health status according to their place in the social hierarchy. Depending on their social status, people face varying levels of exposure and susceptibility to health-compromising circumstances (Williams et al., 2024, WHO, 2010).

For this particular study, the CSDH conceptual framework model was adopted to show how vaccination coverage, zero-dose, dropout and inequality among children in underserved settings of Ethiopia are affected by the interaction between the individual, maternal/caregiver, household, geographical and health infrastructure factors. This helps to better understand the dynamic interrelations among various factors affecting access and utilization of immunization services.

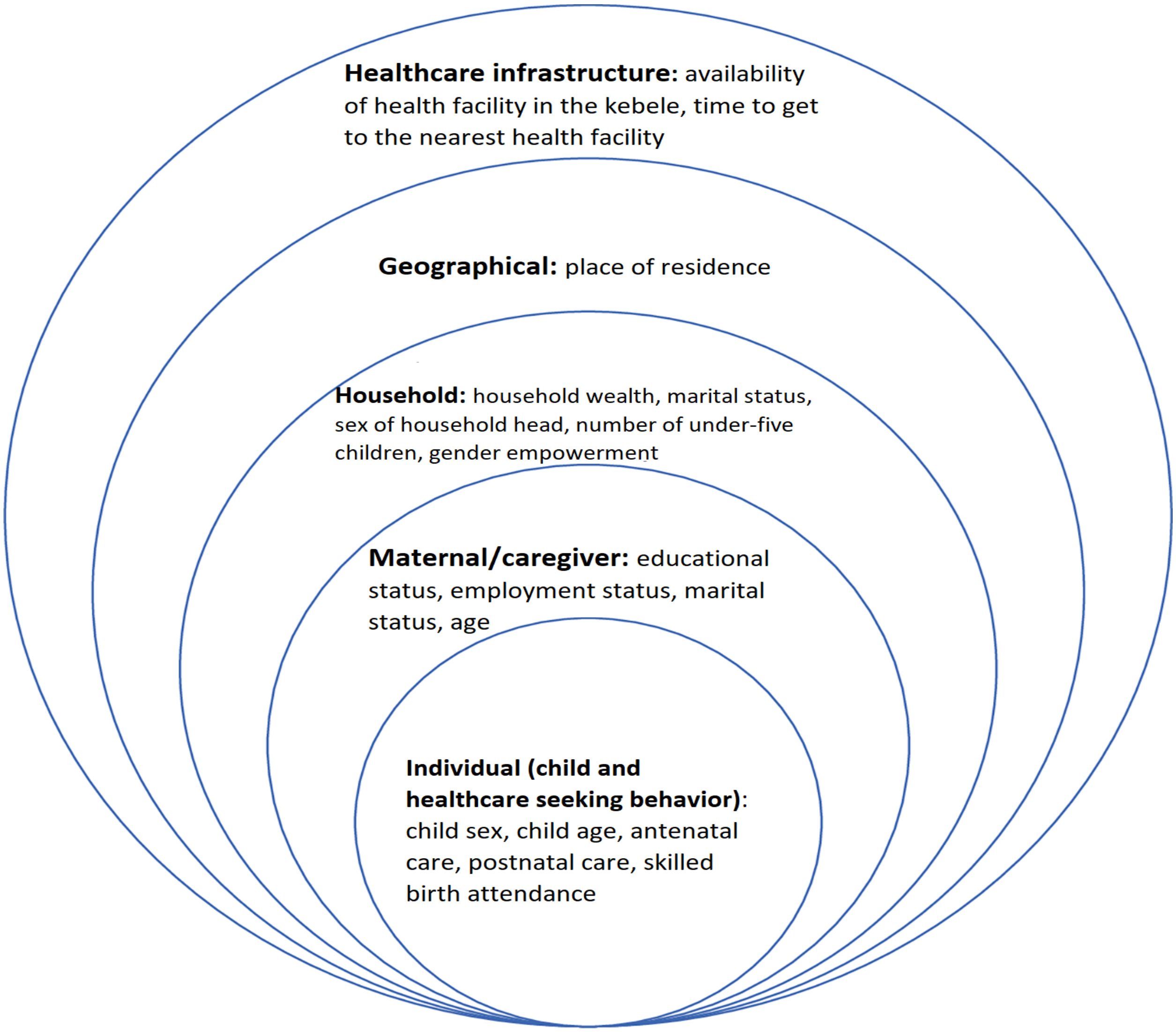

Figure 2: Modified WHO Commission on Social Determinants of Health model

2.6. Structure of the Dissertation

This PhD thesis is prepared as per the guidelines of Dissertation writing by the Department of Pharmaceutics and Social Pharmacy, School of Pharmacy, College of Health Sciences, Addis Ababa University. The thesis is structured into five chapters and four original articles are included.

Chapter I deals with the introductory section. It outlines background information, statement of the problem, the research approach, significance of the study and briefly highlights the overall structure of the thesis. **Chapter II** presents the objectives and research questions. **Chapter III** deals with the methods employed for data collection and analysis. It also briefly describes the study design and settings, study participants, sample size determination, sampling procedure, data collection procedures and data quality assurance, ascertainment of childhood vaccination, variables of the study, data management and statistical analysis.

The major research findings of the four articles are presented in **Chapter IV. Chapter V** discusses the findings of each article. Conclusions and recommendations are presented in this chapter. Strengths and limitations of the research are also described in this chapter. Finally, each published article with an abstract, background, methods, results, discussion, conclusion and/or recommendations and references are added to the thesis.

CHAPTER III: STUDY OBJECTIVES AND RESEARCH QUESTIONS

3.1. Overall objective

The major objective of the study was to estimate vaccination dropout and identify factors, examine socioeconomic inequalities in vaccination dropout, decompose socioeconomic inequalities into the contributions of individual factors and map the spatial distribution of high and low risk areas for zero-dose and measles vaccination dropout children aged 12-35 months in remote and underserved settings of Ethiopia.

3.2. Specific objectives

- To estimate the prevalence of vaccination dropout, identify factors and explain the socioeconomic inequality among children aged 12-35 months in remote and underserved settings of Ethiopia.
- To decompose the concentration index into the contributions of individual factors to wealth related inequalities of childhood vaccination dropout using a decomposition approach
- To map the spatial distribution of zero-dose children aged 12-35 months in remote and underserved settings of Ethiopia
- To estimate the coverage and dropout rate of measles vaccination and map the spatial distribution of high and low risk areas for measles vaccination dropout in remote and underserved settings of Ethiopia.

3.3. Research Questions

- What is the prevalence of childhood vaccination dropout and how does socioeconomic inequality affect vaccination dropout in remote and underserved settings?
- How much does each factor contribute to wealth-related inequalities of childhood vaccination dropout?
- How children who have received zero-dose vaccination are spatially distributed in Ethiopia?
- What is the coverage of measles vaccination and prevalence of measles vaccination dropout? Which areas are hot and cold spot areas for measles vaccination dropout cases?

CHAPTER IV: RESEARCH METHODOLOGY

4.1. Methods

4.1.1. Study design and settings

This study is part of a cross-sectional evaluation survey that was conducted in remote and underserved settings of Ethiopia. The study was implemented following a single round, cross-sectional survey design.

In line with the understanding that nearly half of zero-dose and under-immunized children in low-income countries are from hard-to-reach communities, conflict-affected settings, or disadvantaged urban areas (Gavi, 2021) and based on our analysis of secondary data sources that was done prior to the cross-sectional survey, this study targeted populations in the following eight partly overlapping settings.

Table 1: Target population domains and their descriptions

	Population domain	Description
1	Pastoralist regions and populations	Afar and Somali regions and specific pastoralist or semi-pastoralist settings in Oromia, SNNP, Southwest Ethiopia, and Gambella regions
2	Developing regions	Afar, Somali, Gambella, and Benishangul Gumuz regions
3	Newly-established regions	Sidama and Southwest Ethiopia regions
4	Conflict-affected areas	Selected settings in Afar, Amhara, Oromia, and Benishangul Gumuz regions
5	Underserved urban slums	Urban slums in six selected cities (Addis Ababa, Bahirdar, Hawassa, Dire Dawa, Harar, and Adama) and rural areas under Dire Dawa City Administration and Harari Region
6	Hard-to-reach areas in major regions	Selected remote districts in Amhara, Oromia, and SNNP regions
7	IDPs	Selected IDP centers in Afar, Amhara, Oromia, and Benishangul Gumuz regions
8	Refugees	Refugees from selected camps in Somali, Afar, and Gambella regions

4.1.2. Study participants

The target population are under-five children who resided in underserved, remote, and conflict-affected areas of Ethiopia. All children aged 12-35 months were included as study participants.

4.1.3. Sample size determination

The WHO 2018 immunization coverage cluster survey manual was used as a reference for the sampling design of the study (WHO, 2018b). Adequate sample size for each of the target population was calculated using Cochran's Single Proportion Sample Size Formula (Cochran, 1977) assuming 95% confidence level, 4% margin of error, 16% prevalence of zero-dose children (CSA and ICF, 2016), and 10% compensation for possible non-response. Accordingly, for each of the aforementioned population domains, a sample size of 360 was required. The following sample size formula was used to calculate the number of children required in a prevalence study: $\boldsymbol{n} = \frac{\boldsymbol{Z2p(1-p)}}{\boldsymbol{d2}}$ where n is the total sample size needed, Z is the statistic corresponding to 95% confidence level which is 1.96, P is the prevalence of zero-dose children in previous studies in Ethiopia which is 16%, and d is precision (corresponding to effect size) (Pourhoseingholi et al., 2013). Therefore, a sample size of 360 was required for each of the aforementioned target population domains.

According to the EDHS 2016 and Mini-EDHS 2019 data, an average of 12 children aged 12-35 months of age are available per enumeration area (EA) (EPHI and ICF, 2019, CSA and ICF, 2016). Therefore, for each of the population domains, a minimum of 30 EAs was required to recruit 360 children in each target population 12-35 months, assuming all children in the EA would be eligible for inclusion into the study. In urban slums, 40 EAs were randomly selected and 480 children were drawn (Project HOPE and MOH-Ethiopia, 2022).

Therefore, 4,080 children from 340 EAs (a minimum of 360 sample per population domain) were included in the survey (Table 2). The sample size was large enough to allow subgroup analysis based on sex, age and other pertinent background characteristics including socio-economic status (Project HOPE and MOH-Ethiopia, 2022).

Table 2: Total sample size and EAs required for the quantitative vaccination survey

Types of study population	**Number of EAs**	**Total sample size**
Pastoralist areas in Oromia, SNNP, and Southwest Ethiopia	30	360
Hard-to-reach areas	30	360
Conflict-affected areas	30	360
Refugees	30	360
IDPs	30	360
Newly formed regions: Sidama and Southwest Ethiopia	30	360
Urban slums	40	480
Afar	30	360
Somali	30	360
Benishangul Gumuz	30	360
Gambella	30	360
Total	**340**	**4,080**

4.1.4. Sampling procedure

Children aged 12-35 months were selected using a cluster sampling approach in a two-step procedure. First, EAs were randomly selected from the total EAs available in each target population domain. In this case, the EAs delineated by the Central Statistical Agency (CSA and ICF, 2016) of Ethiopia for the recent census were used as a sampling frame. In the case of urban slums, hotspot urban slums in Addis Ababa, Adama, Bahir Dar, Hawassa, Harar, and Dire Dawa cities were located, delineated, and EA maps were drawn by experienced cartographers. In the case of IDP and refugee camps, villages or clusters were considered as EAs. Second, all eligible children in each EA were listed and 12 children were ultimately selected using a smartphone-based random number generator (Project HOPE and MOH-Ethiopia, 2022).

4.1.5. Data collection procedures and data quality assurance

Data was collected using pretested tools prepared in Amharic, Oromiffa, Somali, Afar, and Sidama languages. Survey data was collected by 48 experienced enumerators and 24 supervisors. Enumerators and supervisors were recruited based on educational status (at least diploma holders in a health-related discipline), previous experience in similar national surveys, and familiarity with electronic data collection tools. Prior to deployment, the enumerators and supervisors received a 5-day training guided by a structured training manual. The training included an explanation on the sampling approach, basic principles of data collection, line-by-line discussion on the questionnaire, mock interviews, field practice, and a review of basic ethical practices of research involving human participants (Project HOPE and MOH-Ethiopia, 2022).

Data collectors were allowed to collect data from up to six individuals per person per day. In order to validate the quality of the data, one third of all the study participants were re-interviewed by the supervisors. The uploaded data was closely monitored by the research team throughout the survey implementation period (Project HOPE and MOH-Ethiopia, 2022).

4.1.6. Ascertainment of childhood vaccination

Three sources of information including caregiver's report, home-based (vaccination cards) reports and facility-based reports were used to determine the vaccination status of children as recommended by the WHO. The child's immunization status was determined by the review of the vaccination card when the mother or caregiver presented it. In the absence of an immunization card, the immunization status was assessed based on the self-reports/recalls of mothers/caregivers. Previous studies have validated the reliability of this method in ascertaining childhood vaccination in resource-limited settings with inadequate documentation of childhood immunization (WHO, 2015).

4.1.7. Variables of the study

The primary outcomes of interest of the study include vaccination dropout, vaccination coverage and zero-dose children. Vaccination dropout is the proportion of children who did not get the subsequent vaccine among those who received the first vaccine. Zero-dose children are those who lack the first dose of DTP1.

Vaccination coverage was calculated as the proportion of children aged 12–35 months who received MCV-1, MCV-2, BCG, Penta-1 or Penta-3 according to the routine immunization schedule of Ethiopia.

Independent variables considered in the current study were selected based on proven relationships from published literatures and their biologically plausible association with the outcome variable. These included wealth index, marital status, child age, respondent age, time to walk to the health facility (one-way), maternal educational status, paternal educational status, caregiver's employment status, ANC visits, postnatal care (PNC) services, place of residence, number of under-five children in a household, skilled birth attendance (SBA), availability of health facility in the kebele (a small administrative unit), gender empowerment, child sex, and sex of household head.

Gender empowerment is a composite index measuring gender inequality in economic participation, decision-making mainly on health-related matters and power over economic resources. Gender empowerment was measured using a composite scale (min=0, max=6). Women's reported power based on six components (major household purchases, expending own income, expending partner's income, visiting families/relatives, and deciding on health care for herself and the index child) was used to develop the scale. Each component was coded as "1" when decision is made by the woman or in joint with her partner and "0" when decision is made solely by the partner. Finally, a score out of 6 was computed and categorized into low (0-2), medium (3or 4) or high (5 or 6) ordinal categories (CSA and ICF, 2016, Project HOPE and MOH-Ethiopia, 2022).

Another composite variable that gauges the woman's household living standards is the wealth index. At the design stage, a representative mix of variables considering the contexts of urban and rural communities were carefully selected. Wealth index was computed as a composite index of living standard as recommended by the DHS Program. It was developed based on ownership of valuable assets and livestock, size of land for agriculture and housing purposes, materials used for house construction, and access to basic social services including electricity, banking, improved water sources, and body waste disposal methods. A total of 41 variables were reduced into nine factors using Principal Component Analysis. The components were further totaled into a score and ultimately divided into five quintiles (poorest, poorer, middle, richer, and richest) (CSA and ICF, 2016, Project HOPE and MOH-Ethiopia, 2022).

4.1.8. Data management and statistical analysis

Data was collected using the CommCare digital app, an open-source and user-friendly application system which is interoperable with major data analytics and visualization software (Dimagi, 2007). The app helped to collect individual child-level and household information to ensure high-quality data collection, cleaning, and monitoring in real time (Project HOPE and MOH-Ethiopia, 2022). Data was then stored in a local server on a daily basis and exported to STATA version 17.0 (StataCorp, 2021) for advanced statistical analysis. The weighted and unweighted sample size was balanced by linearizing post-stratification weights.

Vaccination dropout was assessed using BCG/Penta-1 as the entry vaccine and measles/Penta-3 as the exit vaccine doses. Accordingly, six dropout measures including BCG to Penta-1, BCG to Penta-3, BCG to MCV-1, BCG to MCV-2, Penta-1 to Penta-3 and Penta-1 to MCV-1 were developed. Additionally, a vaccination dropout was computed using MCV-1 as the entry vaccine and MCV-2 as the exit vaccine.

4.1.8.1. Determinants of vaccination dropout rate

A univariable generalized estimating equation analysis was carried out to examine the relationship between the outcome variable and selected independent variables. Then, all potential independent variables with a p-value of ≤ 0.05 in the univariable analysis were fitted into the final generalized estimating equation model. Outputs were summarized using crude odds ratio and adjusted odds ratio (AOR) with 95% confidence interval. A p-value of ≤ 0.05 was considered statistically significant.

4.1.8.2. Vaccination dropout inequality by wealth status

Vaccination dropout inequality by wealth status was estimated using the concentration curve (CC) and CnI. The CC depicts the cumulative percentage of the population, ranked by wealth status, from the poorest to the richest on the x-axis against the cumulative percentage of the dropout status of children on the y-axis. The curve would be aligned with the 45 degrees line if all children had an equal percentage of dropouts regardless of their wealth status, which indicates the presence of equality in vaccination dropout. The CC falling below the 45 degrees line of equality implies that dropout is more concentrated among the rich. The opposite is true if the curve falls above the line of equality. The CnI is a measure of two times the area between the line of equality and the CC. The index is determined by a value between −1 and +1; an index of 0 shows the presence of uniform vaccination dropout between the poor and the rich. Wealth-related inequalities can be observed in one of the two forms. The first is when there is an uneven concentration of dropout among the rich, the CnI takes on a positive value. The second is a CnI taking a negative value that implies a high concentration of vaccination dropout status among the poor. The greater the magnitude of inequality is, the wider the gap will be between the line of equality and the CnI (Bobo and Hayen, 2020).

The CnI can then be measured as follows: twice the covariance of the health variable and the ranking of the living standards variable r all divided by the mean of the health measure (μ). Greater absolute CnI values indicate greater inequality in vaccination dropout.

$$CnI = \frac{2}{\mu} cov\,(h, r) \tag{1}$$

This study makes use of the Erreygers corrected CnI which is algebraically expressed as shown below.

$$E(h) = \frac{4\mu}{b-a} CnI \tag{2}$$

Where μ is the mean of the health variable (vaccination dropout), *CnI* is the standard CnI, with *b* and *a* representing the upper and lower bounds of the outcome variable (h). In our study, the range b–a is unity, as the outcome variable is binary (Erreygers, 2009).

4.1.8.3. Decomposing socioeconomic inequality of vaccination dropout

The values of CnI show and quantify the level of inequalities related to wealth in the use of health services. However, it does not highlight the pathways through which inequality occurs. Policymakers are also interested in the factors that contribute to wealth related inequalities in vaccination dropout. The CnI of a health variable can be decomposed into the contributions of individual factors to the overall level of wealth-related inequalities in childhood vaccination dropout. This can be done using an approach developed by Wagstaff (Wagstaff et al., 2003).

Our health variable *hi* (vaccination dropout), is linked to a set of explanatory variable X_{ij} by the following linear model.

$$hi = \alpha + \sum_{j=1}^{q} (\beta j X j) + \varepsilon\mathrm{i} \tag{3}$$

If we have such linear model as shown in equation (3), Wagstaff et al. shows that the CnI for *hi* can be written as:

$$CnI\ (h) = \sum_{j=1}^{q} \frac{(\beta j \bar{x} j)}{\mu h} \mathrm{CnI\ (Xj)} + \frac{GC\varepsilon}{\mu h} \tag{4}$$

In equation (4), *CnI (h)* is the CnI for the health variable *h* (vaccination dropout), $\bar{x}j$ is the mean of *xj*, μh is the mean of the health variable, *CnI(xj)* is the CnI for *xj,* and $GC\varepsilon$ is the generalised CnI for the error term. In this equation, the first part is the weighted sum of the CnI for the variable *xj*. The weight of each regressor is determined by the elasticity ($\beta\bar{x}j$) of *h* with respect to *xj*. The second part is the residual socioeconomic inequalities in health that cannot be explained by the CnI of the regressors. Since we applied the Erreygers normalisation to the calculation of the CnI for the socio-economic inequalities in vaccination dropout, the corrected CnI for the health variable is formulated as:

$$E\ (h) = 4\ \sum_{j=1}^{q} \beta\text{jXjCnI (Xj)} +\ 4\text{GC}\,\varepsilon \qquad (5)$$

Equation (5) can now be used to decompose socioeconomic inequalities in vaccination dropout, showing the contribution of each factor. If the contribution of variable x is positive, then inequality in the health variable would decrease if variable x becomes equally distributed across the socio-economic group, ceteris paribus. The opposite is also true, if a contribution is negative, the absence of inequalities in that variable would result in an increase in inequality, ceteris paribus. The absolute contribution a variable makes to socioeconomic inequality is a product of the elasticity ($\beta\bar{x}j$) of vaccination dropout for each variable and the CnI for each variable. Therefore, to estimate the contribution, we need to firstly estimate the coefficients of the explanatory variables via a regression. Ordinary Least Squares, Probit, and Generalised Linear Models are the three most common regression methods used for decomposition of inequalities (Wagstaff A et al., 2003, Lauridsen and Pradhan, 2011). The Generalised Linear Model for decomposition of the Erreygers CnI was used in this study. A bootstrapping technique was used to generate the standard errors for the absolute contributions. Data analysis was conducted in STATA 17 and post-stratification sample weights were used in all analysis to adjust for unequal probabilities of selection and non-response.

4.1.8.4. Spatial analysis

The global positioning system (GPS) was recorded to determine the exact location of community clusters with vaccination dropout or zero-dose or partially immunized children. GPS data was collected at each sample cluster and enumeration area. ArcGIS (version 10.8) was used for the spatial analysis. The data was weighted to make the survey representative. In order to balance weighted and unweighted sample size, linearization of post-stratification weights was made. The primary outcome variables in the spatial analysis were zero-dose children and measles vaccination dropout.

4.1.8.5. Spatial autocorrelation

Spatial autocorrelation indicates whether the distribution patterns of zero-dose children and measles vaccination dropout cases across the study area were dispersed, clustered or randomly distributed. The Global Moran's I spatial statistics was used to measure spatial autocorrelation by taking the entire data set. Moran's I is a statistic that produces a single output number between −1 and +1. Moran's I value approaching +1 indicates that zero-dose or measles vaccination dropout children are spatially clustered. Moran's I value approaching −1 indicates a dispersed spatial distribution of zero-dose or measles vaccination dropout children, whereas Moran's I value 0 indicates a random geographic distribution of zero-dose or measles vaccination dropout children. A statistically significant Moran's I test confirms the presence of a significant spatial autocorrelation (p-value <0.05) and leads to rejection of the null hypothesis (zero-dose children or measles vaccination dropout cases are randomly distributed).

4.1.8.6. Hotspot analysis (Getis-Ord Gi statistics)*

The spatial variability of the high and low burden of zero-dose children and measles vaccination dropout cases among children aged 12–35 months were calculated using Getis-Ord Gi* statistics in a hotspot analysis. The statistical significance of clustering was confirmed using the Z-score with a 95% confidence interval and a p-value. Statistical output with a high Gi* shows zero-dose or measles vaccination dropout hotspots, while a low Gi* indicates zero-dose or measles vaccination dropout children cold spots.

4.1.8.7. Spatial interpolation

The spatial interpolation technique was also applied to estimate unknown values that fall between known values. Inverse distance weighting interpolation method was used to predict the risk of zero-dose children.

4.1.8.8. Ethical approval and consent to participate in the study

The research was implemented in compliance with national and international ethical principles. The research protocol was reviewed and approved by the institutional review board of the Ethiopian Public Health Institute (416/2021). Information was collected after receiving written informed consent from the caretakers. To maximize beneficence, all zero-dose children were referred to the nearest health facility using a referral form.

CHAPTER V: KEY FINDINGS

5.1. Sociodemographic Characteristics

A total of 3,646 mothers/caregivers of children between the ages of 12–35 months participated in the study with a response rate of 97.7%. Among the respondents, the majority (59.2%) had no formal education, and over half (54%) were between the ages of 25–34 years. More than 81% came from rural areas, with 17% coming from the Afar region. When the survey was conducted, 57% of the respondents were unemployed, and nearly 91% of the respondents were married or living together.

Table 3: Socio-demographic characteristics of respondents & children in underserved settings of Ethiopia.

Characteristics	Frequency	Percent
Child's sex		
Boy	1,985	54.4
Girl	1,661	45.6
Child's age (months)		
12-23	1,849	50.7
24-35	1,797	49.3
Respondent's age		
15-24	875	24.0
25-34	1,969	54.0
35-44	572	15.7
45 or above	104	2.9
Do not know	126	3.5
Respondent's educational status		
No formal education or preschool	2,158	59.2
Primary education	788	21.6
Secondary education	616	16.9
Tertiary education	84	2.3
Marital status		
Not ever married	43	1.2
Married/Living together	3,312	90.8
Separated	83	2.3
Divorced	110	3.0
Widowed	98	2.7
Place of residence		
Urban	677	18.6
Rural	2,969	81.4
Caregiver's employment status		
Unemployed	2,098	57.6
Employed	1,548	42.4
Region*		
Afar	636	17.4
Amhara	372	10.2
Oromia	431	11.8
Somali	480	13.2
Benishangul Gumuz	216	5.9
SNNP	300	8.2
Sidama	239	6.6
Southwest Ethiopia	181	5.0
Gambella	479	13.1
Harari	60	1.6
Addis Ababa	192	5.3
Dire Dawa	60	1.6
Household size		
2-5	2,044	56.0
6 or above	1,602	44.0

*Unweighted sample size

5.2. Vaccination dropout and wealth related inequality

Childhood vaccination dropout rates were computed using different pairs of antigens. The BCG to Penta-3 (52.5%), BCG to MCV-2 (57.4%), and Penta-1 to Penta-3 (43.9%) dropouts were all high. The highest Penta-1 to Penta-3 dropout rate was found in developing regions (60.1%) and the lowest was in urban slums (11.2%). Caregivers who were working outside their homes [AOR (95% CI) = 3.67 (1.24–10.86)], who had no PNC follow-up visits [AOR (95%CI) = 1.66 (1.15–2.39)], who did not receive a service from an SBA [AOR (95%CI) = 1.64 (1.21–2.27)], who were older than 45 years [AOR (95% CI) = 12.49 (3.87–40.33)], and who were less gender empowered [AOR (95%CI) = 1.63 (1.24–2.15)] had increased odds of Penta-1 to Penta-3 dropout. The odds of dropout for children from poor caregivers was nearly two times higher compared to their wealthy counterparts [AOR (95%CI) = 1.87 (1.38–2.52)]. Inequalities in vaccination dropout were significantly and disproportionately concentrated among the poor (CnI = −0.179; $p < 0.01$). The study also revealed that Addis Ababa city administration had the highest and Gambella region had the lowest vaccination dropout inequalities by wealth.

5.3. Decomposition of socioeconomic inequality

The CnI was used to estimate socioeconomic inequalities in childhood vaccination dropout which was then decomposed to examine the contributing factors to socioeconomic inequalities in vaccination dropout. According to the decomposition analysis, independent variables that contributed the most to socioeconomic inequalities in vaccination dropout include wealth index, place of residence, SBA, and availability of a health facility in the kebele. While wealth index significantly contributed to inequalities in vaccination dropout (49.7%), place of residence also explained -16.2% of the inequality. SBA and availability of a health facility in the kebele were also large contributors to the inequality, contributing 33.6% and 12.6% to inequalities in vaccination dropout, respectively. Furthermore, number of under-five children, sex of the household head, and one-way walking distance to the nearest health facility also contributed 9.4%, 8.4%, and 8.4% to the inequality of vaccination dropout, respectively.

5.4. Measles vaccination coverage and spatial analysis of measles vaccination dropout

Overall, coverages of MCV-1 and MCV-2 were 67% and 35%, respectively. The highest MCV-1 and MCV-2 coverages, 86.8% and 54.1%, respectively, were found in urban slums and with MCV-1 and MCV-2 coverages of 46.4% and 21.2%, respectively, developing regions had the lowest rates. On average, the measles vaccination dropout estimate was 48.3%. Refugees had the highest measles vaccination dropout estimate (56.4%) and urban slums had the lowest measles dropout estimate (37.7%). The hot spot analysis detected the highest burden of measles vaccination dropout in the Afar Region's zones 1 and 5, the Amhara Region's North Gondar Zone, peripheral areas in the Benishangul Gumuz Region's Assosa Zone, the Gambella Region's Agnewak Zone, certain areas of the Harari Region, the Somali Region's Siti Zone, the Oromia Region's West Hararge Zone, the SNNP Region's South Omo Zone, and in certain areas of the Addis Ababa City Administration. On the other hand, most parts of the Oromia, Somali, SNNP, and Amhara regions and the Southwest Ethiopia and Sidama regions were identified as cold spot areas for measles vaccination dropout cases (non-risky areas).

5.5. Spatial distribution of zero-dose children in Ethiopia

The spatial analysis identified that zero-dose children had a significant spatial variation across the study areas and their distribution was non-random (Global Moran's I=0.178971, p< 0.001). According to the hotspot analysis, western, eastern and northern parts of Somali and western and central parts of Afar regions had the highest load of zero-dose children (hotspot areas) followed by the Northeastern part of Amhara and southeastern part of Oromia regions. On the other hand, SNNP, Sidama, and the Eastern part of the Southwest Ethiopia regions were identified as cold spot areas. The spatial interpolation analysis corresponded with the hotspot analysis results where western and central parts of Afar and western, eastern and northern parts of Somali regions were identified as high-risk areas for zero-dose children.

However, Addis Ababa, Dire Dawa, Harari, SNNP, Sidama, Southwest Ethiopia, and parts of Oromia were found to be low-risk areas for zero-dose children.

CHAPTER VI: DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This study was conducted to estimate the prevalence of vaccination dropout and identify factors, examine socioeconomic inequalities in vaccination dropout, decompose socioeconomic inequalities into the contributions of individual factors and map the spatial distribution of high and low risk areas for zero-dose and measles vaccination dropout children aged 12-35 months in remote and underserved settings of Ethiopia. It is the first extensive study on immunization after the two great challenges (COVID-19 and internal conflicts) Ethiopia has recently experienced.

6.1. Discussion

6.1.1. Childhood vaccination dropout and socioeconomic inequality

Although the first and third doses of Pentavalent vaccine are referred to as tracer indicators in the immunization program (WHO, 2018a), other antigens were also used to estimate vaccination dropout. Overall vaccination dropout estimate as well as dropout estimates disaggregated by different population domains were computed, contributing factors for vaccination dropout were identified and inequality of dropout based on wealth status was also examined.

The magnitude of vaccination dropout ranged from 21.3% based on BCG to Penta-1 to 57.4% based on BCG to MCV-2. All the dropout estimates in our study were higher compared to the maximum tolerable dropout level of 10% suggested by the WHO which might be indicative of poor performance of immunization programs in underserved settings of Ethiopia. Vaccination dropout estimates of the present study in the pastoralist population of Ethiopia were also higher compared to dropout estimates from a previous study conducted in the same study settings in Ethiopia. In this study, dropout rates using penta-1 to Penta-3 was 44% and Penta-1 to MCV-1 was 23.1% which are much higher than dropout estimates of a previous study done in the same study setting using same pairs of antigens, which documented rates of 22.1% and 9.0%, respectively (Tessema et al., 2019). In addition, dropout estimates of the present study were higher compared to a dropout estimate of another study (33.1%; Penta-1 to Penta-3) conducted in Jigjiga district, Somali regional state of Ethiopia (Mohamud et al., 2014). The dropout rate in this study (44%) was also higher than 15% as reported in the Mini-EDHS 2019 (Penta-1 to Penta-3) (EPHI and ICF, 2019). The higher dropout rates in the present study might be attributed to the COVID-19 pandemic and internal conflicts.

Globally, childhood vaccination is influenced by parental education (Mora and Trapero-Bertran, 2018, Van Malderen et al., 2013). Our study has also shown that children born from mothers/caregivers and fathers who reported not attending any formal education had higher levels of dropout compared with their counterparts. This is consistent with studies conducted in Nepal, Kenya, Uganda, Guinea Bissau, Ethiopia, Nigeria, and Benin where children of uneducated mothers and fathers reported to have a higher vaccination dropout (Thapa et al., 2021, Haji et al., 2016, Nankabirwa et al., 2010, King et al., 2010, Tadesse et al., 2009, Antai, 2009, Budu et al., 2023). Previous studies from rural India and rural Mozambique also reported that children whose mothers had no schooling were more likely to drop out of vaccination compared with children whose mothers had some years of schooling (Ghosh and Laxminarayan, 2017, Jani et al., 2008, Tesfa et al., 2023). Moreover, our study indicated that children of working mothers/caregivers had a higher likelihood of being dropped out from vaccination programs compared to their counterparts. This is also in line with a study done in Nepal. This might be due to the fact that working mothers have little time to stay with and care for their children (Thapa et al., 2021).

Concur to studies conducted in Pakistan (Imran et al., 2018), Kenya (Van Malderen et al., 2013), and Nigeria (Antai, 2009), the present study showed the inverse relationship between wealth status and vaccination dropout. In this regard, children born from mothers/caregivers who were at the lower level of the wealth quintile had the highest dropout compared to their counterparts. However, a study from

Nepal by Thapa et al. documented a different result that children from middle and rich families reported a higher dropout (Thapa et al., 2021).

The 2016 ANC model of WHO recommends a minimum of eight ANC contacts throughout pregnancy (WHO, 2016b). The present study showed that children born from mothers who had fewer than four or no ANC visits and those who did not seek help from SBAs showed higher dropout rates compared with their counterparts. This might be because ANC contacts provide information about childbirth, newborn care, vaccinations, and the growth of children. In other words, inadequate ANC visits, late visits, or fewer than the recommended number of visits have been correlated with poor newborn health. This finding is supported by other studies conducted in Ethiopia, Nepal, Benin, and in other 69 low- and middle-income countries (Hailu et al., 2022, Thapa et al., 2021, Budu et al., 2023, Kuhnt and Vollmer, 2017).

Children who were born from mothers/caregivers who had no PNC follow up contacts were nearly two times more likely to drop out of vaccination compared to those children who were born from mothers/caregivers who had attended PNC follow-up visits. This finding aligns with a study conducted in North Gondar zone and Laelay Adiabo districts of Ethiopia and a study from Benin which concluded that the likelihood of defaulting from completion of child vaccination was higher among mothers/caregivers who did not attend PNC after birth as compared to those attended at least once (Chanie et al., 2021, Budu et al., 2023, Aregawi et al., 2017). In addition, our results are also consistent with studies conducted in Kenya and Cameroon which showed that failure to attend PNC was a barrier to complete vaccination. The possible explanation of this might be missed opportunity to get advice on the benefits of child vaccination that ultimately leads mothers/caregivers to drop out of child vaccination (Elizabeth et al., 2015, Russo et al., 2015).

In our study, distance to the health facility was found to contribute to vaccination dropout. Closer distance from the mothers'/caregivers' homes to a health facility correlated with lower vaccination dropout rates.

This is consistent with findings from Nigeria, Ethiopia, Kenya, Cameroon, and Mozambique (Hailu et al., 2022, Haji et al., 2016, Russo et al., 2015, Okwaraji et al., 2012, Sato, 2020, Nour et al., 2020b, Shemwell et al., 2017). The study from Kenya showed that residing over 5 km away from a health facility was associated with higher odds of dropping out. Lack of access to health facilities in the neighborhood was also found to contribute to high vaccination dropout. This aligns with results from a community-based participatory research study conducted in Mozambique which found that vaccination dropout was related to a lack of access to healthcare facilities (Powelson et al., 2022, Jani et al., 2008).

The present study has shown that the wealth status of mothers/caregivers contributed to inequality in childhood vaccination dropout. Inequalities in vaccination dropout were disproportionately concentrated among the poor. The negative value (CnI = −0.179) for children who dropped out of vaccination confirms pro-poor distributions. Addis Ababa city administration and Gambella region have the highest and the lowest inequality of vaccination dropout by wealth, respectively. However, this does not mean that Addis Ababa city administration had the highest and Gambella the lowest dropout rates. Although vaccinations are provided free-of-charge in Ethiopia, there are indirect costs that mothers/caregivers are required to pay (for instance, transportation costs) which often limits the uptake of maternal and child health services, including vaccination. In this regard, mothers/caregivers at the lower level of the wealth category are more exposed to such challenges in accessing healthcare facilities, which ultimately leads to vaccination dropout. Our finding is consistent with studies conducted in Nigeria, Benin, and the DRC. According to these studies, existing immunization coverage disparities disproportionately benefited the rich (Ataguba et al., 2016, Antai, 2009, Budu et al., 2023, Lu et al., 2021).

Maternal age was significantly associated with vaccination dropout in the present study. The likelihood of vaccination dropout was twelve times higher among children who were born from mothers/caregivers that were older than 45 years at the time of the survey compared to those children who were born from mothers/caregivers that were younger than 45 years. This is in line with a previous study conducted in Ethiopia (Tesfa et al., 2023). One plausible explanation for this could be that as mothers age, there will be an increase in the number of children they have, which will eventually have an impact on the level of care the children need including vaccination.

It was evident from this study that the odds of vaccination dropout in children from women with low levels of empowerment were 1.63 higher compared to children from women with high levels of empowerment. This aligns with studies conducted in Mozambique and the DRC (Shemwell et al., 2017, Lu et al., 2021).

6.1.2. Decomposition of socioeconomic inequality

The socioeconomic inequality was decomposed into the contributions of individual factors to wealth related inequalities impacting childhood vaccination dropout using a decomposition approach. The overall CnI (-0.179, p<0.01) confirmed the concentration of vaccination dropout among the lowest wealth strata. The study showed that wealth index contributed about 50% of the total inequalities in vaccination dropout. This finding is consistent with studies conducted in low- and middle-income countries (Bobo and Hayen, 2020, Yibeltal et al., 2022, Restrepo-Mendez et al., 2016, Srivastava et al., 2020, Gutierrez and Johri, 2023) where lower dropout rates and improved vaccination coverage are pro-rich. In Benin, an even higher CnI was reported among children from rich homes, emphasizing higher concentration in childhood vaccination among children of the rich (Budu et al., 2023). A study conducted in sub-Saharan Africa showed that countries with lower vaccination coverage had higher inequalities suggesting pro-rich coverage. As a result, they concluded that increasing coverage addresses inequalities (Bobo et al., 2022). However, a study across Gambia (a low-income country), Kyrgyz Republic (a middle-income country), and Namibia (an upper middle-income country) showed the contrary, where receipt of all basic vaccinations was disproportionately concentrated among children from poor households. The lower child vaccination rate among the richer households in Gambia, the Kyrgyz Republic, and Namibia can be due to refusal or lower acceptance of vaccines. The concentration of vaccination among the poor in these three countries might also be attributed to the increased concentration of vaccination in rural as opposed to urban settings (Budu et al., 2023, Payne et al., 2013, Hajizadeh, 2018, Hajizadeh, 2019). Furthermore, in Nigeria and Guinea vaccination dropout was more concentrated among children from the 'most advantaged' backgrounds compared with their counterparts (Wariri et al., 2019).

The other two major contributors to vaccination dropout inequality were SBA (33.6%) and ANC contacts (5.7%). Mothers who had seen SBA and had four or more ANC contacts were concentrated among people of higher socio- economic status with a lower vaccination dropout. This might be because contacts with an SBA provide information about childbirth, newborn care, and immunization (Thapa et al., 2021).

Mothers who had lower educational status were concentrated among people of the lowest wealth strata as indicated by the negative CnI. The contributions of education might be due to the role that it plays in improving maternal health literacy and healthcare utilization behavior. Mothers with higher levels of education are also more likely adhere to the immunization schedule, with a lower dropout rate (Branco et al., 2014, Wondimu et al., 2021, Lauridsen and Pradhan, 2011, Srivastava et al., 2020, Burroway and Hargrove, 2018, Acharya et al., 2019, Forshaw et al., 2017, Balogun et al., 2017, Vikram et al., 2012).

The study has shown that children who were residing in rural areas and who were living in areas where it takes more than 30 minutes to get to the nearest health facility were also concentrated among people of the lowest wealth strata. Place of residence explained -16.2% of the inequality in vaccination dropout. This result is consistent with findings from related studies (WHO, 2021a, Ataguba et al., 2016, Bobo and Hayen, 2020, Lauridsen and Pradhan, 2011, Mohamud et al., 2014, Bangura et al., 2020, Raza et al., 2018). The inequality related to place of residence could partly be explained by challenges faced in rural areas due to less developed health infrastructure and fewer skilled providers. In rural areas, traveling long distances to get health facilities is another reason for low basic vaccination coverage and high dropout. In addition, lack of transportation access, travel costs, and waiting time pose critical challenges for mothers to take their child for vaccination (Wondimu et al., 2021, WHO, 2016a). Vaccines are transported and stored in cold chain as they can easily be damaged by high temperatures (Kartoglu and Milstien, 2014). However, health facilities in rural areas face a shortage of electric power supply to keep the cold chain equipment working which could impede provision of vaccination services as a result of stockout of vaccines (McGavin et al., 2018). Vaccine and supplies stockouts also contributed to the problem (Zewdie et al., 2016). Non-functionality of fridges for vaccine storage could also affect the provision of vaccination services (Ophori et al., 2014). To the contrary, a study in Ghana showed that children in rural areas were more likely to complete the required vaccinations which might be attributed to the expansion of primary healthcare in rural Ghana (Asuman et al., 2018).

6.1.3. Measles vaccination coverage and spatial analysis of measles vaccination dropout

AFR countries and partners planned to achieve ≥95% with two doses of MCV coverage. However, these goals were not met and, in 2021, coverages of MCV-1 and MCV-2 remained <95%. To reach the updated 2030 regional measles elimination target in at least 80% of African countries, it is imperative to administer both doses of the measles vaccine to every child and enhance surveillance (Masresha et al., 2023). Estimating the coverage of measles vaccination and understanding the geographical distribution of measles vaccination dropout is crucial to setting up appropriate interventions.

The coverage of childhood MCV-1 and MCV-2 were 67% and 35%, respectively, which were higher than the estimates from secondary analysis of the Mini-EDHS 2019 data of 59% for MCV-1 (Masresha et al., 2023, Tesfa et al., 2022) and 12% for MCV-2 (Muluneh et al., 2022). However, the MCV-2 coverage from our study was lower than the finding presented in the 2022 joint report of the WHO and UNICEF (48%)

(WHO, 2021b). Our study's inclusion of underprivileged areas could possibly explain this discrepancy between MCV-2 coverage estimates.

The measles vaccine coverage estimates differed amongst the various population domains. Among these target populations, urban settings had the highest MCV-1 and MCV-2 coverage estimates. Compared to previous studies in urban areas, the MCV-2 coverage showed a modest improvement. For instance, the estimated coverage of MCV-2 in underserved urban areas of the present study was 54.1% which was higher than the coverage in urban areas of the North Shoa Zone in central Ethiopia (42.5%) (Tadesse et al., 2022). The current study's childhood MCV-1 and MCV-2 coverages were still far below the recommended herd immunity threshold (95%) necessary to achieve high population immunity against measles. This indicates that Ethiopia and the AFR are still at high risk for measles outbreaks (Geremew et al., 2019).

Measles vaccination dropout rate overall was estimated to be 48.3%. This was higher than the vaccination dropout estimates from the same study looking at penta-1 to penta-3 (44%) and BCG to MCV-1 (21.5%). Similar to the vaccination coverage results, the measles vaccination dropout estimates varied across the different target populations. Higher measles vaccination dropout estimates were found in refugees (56.4%), pastoralist populations (54.3%), developing regions (54.4%), and newly established regions (53.5%), whereas the lowest estimate was in urban slums (37.7%). These findings are in line with a previous study that reported higher dropout estimates in pastoralist regions (Tessema et al., 2019). The delayed introduction of MCV-2 into Ethiopia's routine immunization program in 2020 might have contributed to the increased MCV-1 to MCV-2 dropout estimate. Moreover, a lack of awareness of the need to return for MCV-2 may have also led to a higher dropout estimate (Tadesse et al., 2022). All the measles vaccination dropout estimates of the present study were higher compared to the WHO's 10%

maximum acceptable dropout threshold. This could be a sign of the immunization programs' inadequate performance in Ethiopia's underprivileged areas (Mmanga et al., 2022, Hailu et al., 2022).

Mapping the spatial heterogeneity of childhood vaccination is becoming more and more important to donors and policymakers so they can pinpoint any gaps and take appropriate action. The global spatial autocorrelation analysis of our data showed a clustering pattern of childhood measles vaccination dropout cases across the study areas (Global Moran's I = 0.992195, $p < 0.001$). This indicated that measles vaccination dropout cases were aggregated in specific areas. The hot spot analysis showed that the highest burden of measles vaccination dropout cases (hot spot areas) were detected in zones 1 and 5 of the Afar Region, the North Gondar Zone of the Amhara Region, peripheral areas in the Assosa Zone of the Benishangul Gumuz Region, the Agnewak Zone of the Gambella Region, certain areas of the Harari Region, the Siti Zone of the Somali Region, the West Hararge Zone of the Oromia Region, the South Omo Zone of the SNNP Region, and certain areas of the Addis Ababa City Administration.

The hot spot analysis's results are in line with earlier surveys and studies carried out in Ethiopia. A study on the spatial distribution of immunization defaulting in Ethiopia showed that most defaulters were in the eastern and northeastern parts of the country (Awol et al., 2021). A previous literature also indicated that areas with low immunization were spatially clustered in the northeastern parts of the country (EPHI and ICF, 2019, Ketema et al., 2020, Atalell et al., 2022b, Atalell et al., 2022a). Moreover, two separate studies by Tesfa et al. also showed the presence of low vaccination clusters in zones 1, 4, and 5 of the Afar Region and the Liben Zone of the Somali Region (Tesfa et al., 2023, Tesfa et al., 2022). The high burden of measles vaccination dropout cases in northeastern parts of Ethiopia was attributed to the nomadic and pastoralist populations that move from place to place seasonally, negatively inhibiting access to health care services, including immunization (Lakew et al., 2015, Tamirat and Sisay, 2019, Nour et al., 2020a, Sheik-Mohamed and Velema, 1999). Low utilization of health information in these parts of Ethiopia might also contribute to the high burden of measles vaccination dropout cases (Teklegiorgis et al., 2014). On the other hand, most parts of Addis Ababa, Oromia, Somali, SNNP, and Amhara regions and Southwest Ethiopia and Sidama regions were identified as cold spot areas for measles vaccination dropout cases (non-risky areas).

6.1.4. Spatial distribution of zero-dose children in Ethiopia

One critical component for evidence-based decision-making in the prevention and control of vaccine-preventable diseases is understanding the variations in vaccination coverage. Detecting spatial heterogeneity is useful in indicating existing programmatic gaps affecting progress that could not be identified through the routine monitoring of vaccination coverage (WHO, 2012). To our knowledge, this is the first study to map the spatial distribution of zero-dose children in Ethiopia.

A hotspot analysis of the data revealed that the western and central parts of Afar, as well as the western, eastern, and northern parts of Somalia, were home to a high concentration of zero-dose children. The hotspot analysis results, which identified western and central parts of Afar as well as western, eastern, and northern parts of Somalia as high-risk areas for zero-dose children, were consistent with the spatial interpolation analysis results. Conversely, cold spot areas were observed in Addis Ababa, Dire Dawa, Harari, SNNP, Sidama, and the Eastern part of Southwest Ethiopia.

The results of our study, which examined the spatial distribution of zero-dose children in Ethiopia, are in line with other similar studies carried out in Ethiopia as well as studies that further analyzed the EDHS datasets from 2016 and 2019. These studies showed that the spatial clustering of low immunization coverage was observed in the Eastern and Northeastern parts of the country (EPHI and ICF, 2019, Tesfa et al., 2023, Tesfa et al., 2022, Ketema et al., 2020, Atalell et al., 2022a, Asmare et al., 2022). Furthermore, a study done on the geographical variations of immunization defaulting in Ethiopia also showed that most of the hotspot areas (high default value) were located in the eastern (Somali) and northeastern (Afar) parts of the country, whereas most cold spot areas (low default rates) were located in Addis Ababa, Dire

Dawa, and Harari (Awol et al., 2021). Our findings also aligned with the geographical distribution of low childhood measles-containing vaccine coverage where significant clusters were detected primarily in Afar and Somali regions (Tesfa et al., 2022, Geremew et al., 2019).

There could be several explanations for the high number of zero-dose children in the Somali and Afar regions. These include living in pastoralist and developing regions, mothers'/caregivers' lack of or lower educational status, unavailability of public health facilities, and suboptimal healthcare-seeking behavior. In addition, lower immunization coverage and vaccine uptake might also contribute to the high burden of zero-dose children in these regions. Moreover, these regions have areas that are hard to reach with nomadic and pastoralist inhabitants who do not have permanent residences (Lakew et al., 2015, Tamirat and Sisay, 2019, Nour et al., 2020a). According to findings of a study that was part of the same cross-sectional survey with the present one, inadequate information being provided by health workers, irregularities in service provision, suboptimal staff motivation, high staff turnover, closure and inaccessibility of health facilities, lack of functional health posts, service provision limited to selected days or hours, and gender norms viewing females as responsible for childcare, religious beliefs, cultural norms, fear of vaccine side effects, and lack of awareness and sustained interventions were associated with the high proportion of zero-dose children in underserved settings of Ethiopia (Biks et al., 2024a).

The existing health care systems are in the hands of settled populations and rarely have access to nomads due to cultural, political and economic obstacles. Nomadic and pastoralists populations also move seasonally from place to place, which negatively inhibits access to health care services, including immunization (Sheik-Mohamed and Velema, 1999). Low utilization of health information, religious beliefs, cultural norms, fear of vaccine side effects and lack of awareness and sustained interventions (Mekonnen and Gebeyehu, 2021) in these parts of Ethiopia might also contribute to the high burden of zero-dose children.

Strengths and Limitations

This study had a number of noteworthy strengths. Information gathered from various sources was used to determine childhood vaccination status. Vaccination cards, medical records, and mothers'/caregivers' recall were used to ascertain vaccination dropout. The results were validated and verified by triangulating these three sources. Acquiring high-quality data was made possible through the use of digital tools and skilled data collectors. Despite the presence of active conflicts in certain study areas, the research team was able to gather data in those areas.

The study's utilization of advanced statistical analysis techniques such as decomposition and geospatial analyses is another strength. Decomposition of socioeconomic inequalities would be of paramount importance for policymakers to address the socioeconomic disparities that exist around childhood vaccination coverage and dropout in Ethiopia. Identified hotspot areas for zero-dose and measles vaccination dropout children could be used as a baseline to reduce vaccination dropout in underserved settings of Ethiopia.

However, the study had also limitations including its incapacity to draw conclusions about causality and its vulnerability to biases such as nonresponse bias and recall bias, which are directly linked to the study design i.e., cross-sectional. For IDPs and refugee settings, if an immunization card was not available, the only way to determine a child's immunization status was through mothers'/caregivers' self-reports/recalls. In this case, misclassification may result from mothers/caregivers who lack vaccination cards forgetting their children's vaccination status. In addition, respondents' social desirability bias might have underestimated the prevalence of vaccination dropout and zero-dose children.

Conclusion and recommendations

Vaccination dropout estimates were high among children residing in remote, underserved, and conflict affected settings of Ethiopia. Factors that contributed the most to socioeconomic inequalities in vaccination dropout were wealth index, place of residence, SBA, and availability of a health facility in the kebele. Childhood vaccination dropout was concentrated among the relatively poorer families.

The overall MCV-1 and MCV-2 coverage estimates were low, measles vaccination dropout was high, and there were geographical variations in both parameters across Ethiopia. The hot spot analysis showed that the highest burdens of measles vaccination dropout cases were detected mainly in the northeastern parts of Ethiopia and high clusters of zero-dose children were detected in western and central parts of Afar and western, eastern and northern parts of Somali regions.

Strengthening horizonal integration of immunization services with maternal & child health services such as ANC and PNC, sick childcare, nutritional screening, growth monitoring, oral rehydration therapy training sessions, vitamin A supplementation and family planning would reduce missed opportunities for vaccination i.e. children who are eligible for vaccination but do not receive one or more of the vaccine doses. Empowering women is also another vehicle to reduce vaccination dropout. Strengthening static and outreach campaigns, supplementary immunization activities, periodic intensification of routine immunization in remote and underserved areas will help reduce vaccination dropout and zero-dose children. Policymakers in Ethiopia need to address the disproportionate concentration of vaccination dropout among the poor by strengthening women's utilization of healthcare services and the accessibility of health facilities in rural kebeles.

Due to its recent introduction, the lack of awareness around MCV-2 needs to be addressed in Ethiopia, especially in the northeastern part of the country where there were the highest clusters of measles vaccination dropout cases.

Generally, the study might contribute to achieving the IA2030 aimed at providing effective and equitable vaccines to everyone, everywhere in the world to realize better health and well-being through avoiding vaccine-preventable diseases.

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Vaccination dropout and wealth related inequality among children aged 12–35 months in remote and underserved settings of Ethiopia: a cross-sectional evaluation survey

Fisseha Shiferie[1,2]*, Samson Gebremedhin[3], Gashaw Andargie[1], Dawit A. Tsegaye[1], Wondwossen A. Alemayehu[4], Legese Alemayehu Mekuria[1], Tamiru Wondie[1] and Teferi Gedif Fenta[2]

[1]Project HOPE Ethiopia Country Office, Addis Ababa, Ethiopia, [2]School of Pharmacy, Addis Ababa University, Addis Ababa, Ethiopia, [3]School of Public Health, Addis Ababa University, Addis Ababa, Ethiopia, [4]Project HOPE Headquarter, Washington, DC, United States

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EDITED BY
Valeriane Leroy,
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Sidikiba Sidibe,
Gamal Abdel Nasser University of Conakry, Equatorial Guinea

*CORRESPONDENCE
Fisseha Shiferie
✉ fshiferie@projecthope.org

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Background: Vaccination is one of the most cost-effective public health interventions that prevents millions of deaths. Although immunization coverage is increasing globally, many children in low- and middle-income countries drop out of the vaccination continuum. This study aimed at determining vaccination dropout rates and predictors in children aged 12–35 months in remote and underserved areas of Ethiopia.

Methods: This study was part of a cross-sectional evaluation survey that was conducted in 2022 in Ethiopia. The study settings include pastoralist, developing & newly established regions, conflict affected areas, urban slums, internally displaced populations and refugees. A sample of 3,646 children aged 12–35 months were selected using a cluster sampling approach. Vaccination dropout was estimated as the proportion of children who did not get the subsequent vaccine among those who received the first vaccine. A generalized estimating equation was used to assess determinants of the dropout rate and findings were presented using an adjusted odds ratio with 95% confidence interval. Concentration curve and index were used to estimate wealth related inequality of vaccination dropout.

Results: A total of 3,646 caregivers of children participated in the study with a response rate of 97.7%. The BCG to Penta-3 (52.5%), BCG to MCV-2 (57.4%), and Penta-1 to Penta-3 (43.9%) dropouts were all high. The highest Penta-1 to Penta-3 dropout rate was found in developing regions (60.1%) and the lowest was in urban slums (11.2%). Caregivers who were working outside their homes [AOR (95% CI) = 3.67 (1.24–10.86)], who had no postnatal care follow-up visits [AOR (95%CI) = 1.66 (1.15–2.39)], who did not receive a service from a skilled birth attendant [AOR (95%CI) = 1.64 (1.21–2.27)], who were older than 45 years [AOR (95% CI) = 12.49 (3.87–40.33)], and who were less gender empowered [AOR (95%CI) = 1.63 (1.24–2.15)] had increased odds of Penta-1 to Penta-3 dropout. The odds of dropout for children from poor caregivers was nearly two times higher compared to their wealthy counterparts [AOR (95%CI) = 1.87 (1.38–2.52)].

Abbreviations
ANC, antenatal care; PNC, postnatal care; EPI, expanded programme for immunization; AOR, adjusted odds ration; COR, crude odds ratio; BCG, cacillus calmette–guérin; MCV, measles; CSA, central statistical agency; DHS, demographic and health survey; EA, enumeration area; SBA, skilled birth attendant; CCI, concentration index; IDPs, internally displaced populations; SNNP, southern nations, nationalities, and peoples.

Conclusion: Vaccination dropout estimates were high among children residing in remote and underserved settings. Poor wealth quintile, advanced maternal age, low women empowerment, and limited utilization of maternity care services contributed to vaccination dropout.

KEYWORDS

vaccination, dropout rate, inequality, remote, underserved, Ethiopia

1. Introduction

Vaccination is one of the most important and cost-effective public health interventions that prevents millions of deaths annually. Even though immunization coverage is increasing globally, many children in low- and middle-income countries drop out of the vaccination continuum (1–3). The global coverage of immunization dropped from 86% in 2019 to 81% in 2021 (4).

In 2021, 25 million children were zero-dose (missing Penta-1) or under-vaccinated (missing Penta-3) (5). In 2019, 19.7 million children worldwide did not receive the third dose of vaccination against diphtheria, tetanus, and pertussis in their first year of life, a crucial sign of the effectiveness of immunization programs. Every year, 4.4 million children in sub-Saharan Africa die from communicable diseases that could be prevented by vaccination (6).

The Expanded Programme for Immunization (EPI) of Ethiopia is currently administering 11 different antigens to infants born in the country each year. The vaccination service is mainly provided in health centers and health posts through a combination of static, outreach, and mobile activities. Polio, measles, and meningitis vaccines are also being administered by large-scale periodic campaigns (7).

A study conducted in pastoral and semi-pastoral regions of Ethiopia revealed that 20.5% of children who received at least one vaccine did not take at least one of the subsequent doses. The dropout rate between pentavalent 1 and measles vaccinations was 14.1% followed by BCG and measles (10.1%), both of which are above 10%, the WHO maximum tolerable dropout rate (8).

Vaccination dropout refers to the proportion of children who did not get the subsequent vaccine among those who received the first vaccine. It is determined by calculating the proportion of children who dropped out from the immunization system between Penta-1 and Penta-3 or Penta-1 and MCV-1 (9, 10) or BCG and MCV-1, BCG and MCV-2, BCG and Penta-1, or BCG and Penta-3. Dropout rate can also be determined by using BCG as the entry vaccine and measles as the exit vaccine (proportion of children who did not get measles antigen among those who received BCG (10). Vaccination dropout rates are utilized to measure the continuity of the immunization program for children. According to the WHO, a dropout rate of >10% is unfavorable and indicates that a health facility has limitations in utilization. In contrast, a low dropout rate is indicative of good utilization and therefore of good service quality (11–13).

Gavi's 5.0 Strategy is guided by a "missed communities, first priority" principle to prioritize children missing vaccinations, particularly those found in displaced and vulnerable communities. Almost half of these missed children reside in fragile and conflict-affected settings. Studies focused on immunization, including dropout, have not been extensively conducted in underserved settings including pastoralist regions, developing regions, newly established regions, conflict affected areas, underserved urban populations, internally displaced populations (IDPs), and refugee populations, especially after the two great challenges (COVID-19 and internal conflicts) Ethiopia has recently experienced. Hence, this study was conducted to estimate the prevalence of vaccination dropout, identify associated factors and explain the socioeconomic inequality in children aged 12–35 months in remote and underserved areas of Ethiopia.

2. Methods

2.1. Study design and settings

This study was part of a cross-sectional national evaluation survey that was conducted from May to July 2022. Prior to the quantitative survey, zero-dose and under-immunized areas were identified through qualitative situational and geospatial analyses based on secondary data sources. The study was implemented following a single round, cross-sectional survey design.

Considering that almost half of zero-dose and under-immunized children in low-income countries are located in hard-to-reach communities, conflict-affected settings, or disadvantaged urban areas (14), the study focused on populations in the following eight partly overlapping settings.

1. Pastoralist regions and populations: Afar and Somali regions, and specific pastoralist or semi-pastoralist settings in Oromia, Southern Nations, Nationalities, and Peoples (SNNP), Southwest Ethiopia Peoples, and Gambella regions.
2. Developing regions: Afar, Somali, Gambella, and Benishangul Gumuz regions.
3. Newly established regions: Sidama and Southwest Ethiopia Peoples regions.
4. Conflict affected areas: Selected settings in Afar, Amhara, Oromia, and Benishangul Gumuz regions.
5. Underserved urban populations: Urban slums in six selected cities (Addis Ababa, Bahirdar, Hawassa, Dire Dawa, Harar, and Adama) and rural areas under Dire Dawa City administration and Harari region.
6. Hard-to-reach areas in major regions: Selected remote districts in Amhara, Oromia, and SNNP regions.

7. IDPs: Selected IDP centers in Afar, Amhara, Oromia, and Benishangul Gumuz regions.
8. Refugees: Refugees from selected camps found in Somali, Afar, and Gambella regions (15).

2.2. Study participants

The target population were children under five years of age who lived in underserved, remote, and conflict-affected areas of Ethiopia. Children between the ages of 12 and 35 months were included in the study.

2.3. Sample size determination

The sampling design of the study was adopted from WHO's 2018 immunization coverage cluster survey manual (16). The Cochran's Single Proportion Sample Size Formula was employed to calculate the appropriate sample size for each target population (17) assuming 95% confidence level, 4% margin of error, 16% prevalence of zero-dose children (18), and 10% compensation for possible non-response. The following sample size formula was used to calculate the number of children required in a prevalence study: $n = \frac{Z2p(1-p)}{d2}$ where n is the total sample size needed, Z is the statistic corresponding to 95% confidence level which is 1.96, P is the prevalence of zero-dose children in previous studies in Ethiopia, and d is precision (corresponding to effect size) (19). Thus, it was necessary to have a sample size of 360 for each target population domains.

The Ethiopian DHS 2016 and Mini DHS 2019 data indicate that each enumeration area (EA) has an average of 12 children aged 12–35 months (18). Therefore, a minimum of 30 EAs were required for each population domain to recruit 360 children in each target population within 12–35 months, assuming that all children in the EA would be eligible for inclusion into the study. In urban slums, 40 EAs were randomly selected and 480 children were drawn (15).

The original plan was to include 4,080 children from 340 EAs (at least 360 samples per population domain) in the survey. Due to security concerns in certain study districts, 3,646 children aged 12–35 months from 340 EAs were enrolled in the actual survey. The total sample size was sufficient to enable subgroup analysis based on sex, age and other relevant background characteristics, including socioeconomic status (15).

2.4. Sampling procedure

A two-step procedure was employed to select children aged 12–35 months using a cluster sampling approach. The first step was to randomly select EAs from the total EAs available in each target population domain (15). The sampling frame used was the EAs delineated by the Central Statistical Agency (18) of Ethiopia for the recent census. In the case of urban slums, hotspot urban slums in Addis Ababa, Adama, Bahir Dar, Hawassa, Harar, and Dire Dawa cities were located, delineated, and EA maps were drawn by experienced cartographers. In the case of IDP and refugee camps, villages or clusters were considered as EAs. The second step was to list all eligible children in each EA and then select 12 children using a smartphone-based random number generator (15).

2.5. Data collection procedures and data quality assurance

Data were collected using pretested tools prepared in Amharic, Afan Oromo, Somali, Afar, and Sidama languages. Survey data were collected by 48 experienced enumerators and 24 supervisors using the CommCare digital app, an application system that is open-source, user-friendly, and compatible with major data analytics and visualization software. The CommCare app was utilized to gather information about individual children and households to guarantee high-quality data collection, cleaning, and monitoring in real time (20).

The recruitment process for enumerators and supervisors was based on their educational status (at least diploma holders in a health-related discipline), past experience in similar national surveys, and familiarity with the CommCare digital app (20). The enumerators and supervisors received a 5-day training before deployment that was guided by a structured training manual. The training covered the sampling approach, basic data collection principles, a line-by-line discussion of the questionnaire, an introduction to utilizing the CommCare digital app, mock interviews, field exercises, and an overview of basic ethical research practices that involves human subjects (15).

Data collectors were permitted to collect data from as many as six individuals per person per day. The quality of the data was verified by re-interviewing a third of all the study participants by the supervisors. Throughout the survey implementation period, the research team was closely monitoring the uploaded data (15).

2.6. Ascertainment of childhood vaccination

Three sources of information, including caregiver's report, home-based (vaccination cards) reports, and facility-based reports, were used to determine the vaccination status of children, as recommended by the WHO. The child's immunization status was determined by the review of the vaccination card when the mother or caregiver presented it. In the absence of an immunization card, the immunization status was assessed based on the self-reports/recalls of mothers/caregivers. Previous studies have validated the reliability of this method in ascertaining childhood vaccination in resource-limited settings with inadequate documentation of childhood immunization (20, 21).

2.7. Variables of the study

The primary outcome of interest of the study was vaccination dropout which is the proportion of children who did not get the subsequent vaccine among those who received the first vaccine.

The predictor variables included wealth index, marital status, child age, respondent age, time to walk to the health facility (one-way), maternal educational status, paternal educational status, caregiver's employment status, antenatal care visits, postnatal care (PNC) services, place of residence, number of under-five children, skilled birth attendance (SBA), availability of health facility in the kebele (a small administrative unit), gender empowerment, child sex, and sex of household head.

Gender empowerment is a composite index measuring gender inequality in economic participation, decision-making mainly on health-related matters and power over economic resources.

The wealth index, which is a composite variable, measures the woman's household living standards. As per the DHS program's recommendation, it was calculated as a composite index of living standards. The wealth index was created based on the ownership of valuable assets and livestock, the land size for agriculture and housing purposes, materials used to construct homes, availability and access to basic social services such as electricity, banking, improved water sources, as well as methods for disposing of body waste. By using Principal Component Analysis, a total of 41 variables were reduced to nine factors. The components were combined into a score and then split into five quintiles (poorest, poorer, middle, richer, and richest) (15, 18).

2.8. Data management and statistical analysis

Data was collected using the CommCare digital app (22) and stored in a local server on a daily basis. It was exported to STATA version 17.0 (23) for advanced statistical analysis. The weighted and unweighted sample size was balanced by linearizing post-stratification weights.

Vaccination dropout was assessed using BCG as the entry vaccine and measles/Pentavalent as the exit vaccine doses. Accordingly, four dropout measures including BCG to Penta-1, BCG to Penta-3, BCG to MCV-1, and BCG to MCV-2 were developed. Additionally, two vaccination dropout measures that included Penta-1 to Penta-3 and Penta-1 to MCV-1 were computed using Penta-1 as the entry vaccine and Penta-3/or MCV-1 as the exit vaccine doses. Vaccination dropout was calculated as the proportion of children who did not get the subsequent vaccine among those who received the first vaccine.

In the immunization program, the first and third doses of Pentavalent vaccine are considered as tracer indicators (24). In the present study, the statistical analyses were performed using the Penta-1 to Penta-3 vaccination dropout estimate as an outcome variable i.e., the proportion of children who did not receive Penta-3 among those who received Penta-1.

The outcome variable is whether a child had dropped out of the third dose of Pentavalent vaccine. Predictor variables considered in the current study were selected based on proven relationships and predicting factors from published literatures and their biologically plausible association with vaccination dropout. These included wealth status, marital status, child age, respondent age, time to walk to health facility (one-way), maternal educational status, paternal educational status, caregiver's employment status, ANC visits, PNC services, place of residence, number of under-five children, SBA, availability of health facility in the kebele, gender empowerment, child sex, and sex of household head. A univariable generalized estimating equation analysis was carried out to examine the relationship between the outcome variable and selected predictor variables. Then, all potential predictors with a *p*-value less than 0.05 in the univariable analysis were fitted into the final generalized estimating equation model. Outputs were summarized using crude odds ratio (23) and adjusted odds ratio (AOR) with 95% confidence interval (25). A *p*-value of ≤ 0.05 was considered statistically significant.

2.8.1. Vaccination dropout inequality by wealth status

Vaccination dropout inequality by wealth status was estimated using the Concentration Curve and Concentration Index (CCI). The concentration curve depicts the cumulative percentage of the population, ranked by wealth status, from the poorest to the richest on the x-axis against the cumulative percentage of the dropout status of children on the y-axis. The curve would be aligned with the 45 degrees line if all children had an equal percentage of dropouts regardless of their wealth status, which indicates the presence of equality in vaccination dropout. The concentration curve falling below the 45 degrees line of equality implies that dropout is more concentrated among the rich. The opposite is true if the curve falls above the line of equality. The concentration index is a measure of two times the area between the line of equality and the concentration curve. The index is determined by a value between −1 and +1; an index of 0 shows the presence of uniform vaccination dropout between the poor and the rich. Wealth-related inequalities can be observed in one of the two forms. The first is when there is an uneven concentration of dropout among the rich, the concentration index takes on a positive value. The second is a concentration index taking a negative value that implies a high concentration of vaccination dropout status among the poor (26).

The CI can then be measured as follows: twice the covariance of the health variable and the ranking of the living standards variable r all divided by the mean of the health measure (μ). Greater absolute CI values indicate greater inequality in vaccination dropout.

$$CI = \frac{2}{\mu} \mathrm{cov}\ (\mathrm{h}, \mathrm{r})$$

This study utilizes the Erreygers corrected concentration index that is algebraically expressed as shown below.

$$E(h) = \frac{4\mu}{\mathrm{b} - \mathrm{a}} CI$$

Where μ is the mean of the health variable (vaccination dropout), *CI* is the standard CI, with b and a representing the upper and lower bounds of the outcome variable (h). In our study, the range b–a is unity, as the outcome variable is binary (27).

3. Results

3.1. Sociodemographic characteristics

A total of 3,646 mothers/caregivers with children aged 12–35 months participated in the study with a response rate of 97.7%. Over half of (54%) respondents were between 25 and 34 years of age and the majority of them (59.2%) had no formal education. More than 81% of respondents were from rural areas and 17% of them were from Afar region. Nearly 91% of the respondents were married/living together and 57% were unemployed at the time of the survey (**Table 1**).

TABLE 1 Socio-demographic characteristics of respondents and children in underserved settings of Ethiopia, 2022.

Characteristics	Frequency	Percent
Child's sex		
Boy	1,985	54.4
Girl	1,661	45.6
Child's age (months)		
12–23	1,849	50.7
24–35	1,797	49.3
Caregiver's age		
15–24	875	24.0
25–34	1,969	54.0
35–44	572	15.7
45 or above	105	2.9
Do not know	126	3.5
Caregiver's educational status		
No formal education or preschool	2,158	59.2
Primary education	788	21.6
Secondary education	616	16.9
Tertiary education	84	2.3
Marital status		
Not ever married	43	1.2
Married/Living together	3,312	90.8
Separated	83	2.3
Divorced	110	3.0
Widowed	98	2.7
Place of residence		
Urban	677	18.6
Rural	2,969	81.4
Caregiver's employment status		
Unemployed	2,098	57.6
Employed	1,548	42.4
Region[a]		
Afar	636	17.4
Amhara	372	10.2
Oromia	431	11.8
Somali	480	13.2
Benishangul Gumuz	216	5.9
Southern Nations Nationalities and peoples	300	8.2
Sidama	239	6.6
Southwest Ethiopia	181	5.0
Gambella	479	13.1
Harari	60	1.6
Addis Ababa	192	5.3
Dire Dawa	60	1.6
Household size		
2–5	2,044	56.0
6 or above	1,602	44.0

[a]Unweighted sample size.

3.2. Childhood immunization

Of the 3,646 children, nearly 71% had received BCG. The proportion of children who had received the first dose of Pentavalent vaccine was 68% and 39% of them had received the third dose of the pentavalent vaccine. **Table 2** below shows the number of children who had received various antigens against common childhood illnesses according to vaccination cards, medical records, or caregivers' self-reports.

3.3. Vaccination dropout estimates in remote and underserved settings of Ethiopia

Vaccination dropout estimates varied across the different pairs of antigens, target populations, and the type of measurement methods used. Overall, the highest vaccination dropout estimate was 57.4% based on BCG and MCV-2 vaccines, whereas the lowest dropout was 21.3% for BCG to Penta-1 pairs (**Figure 1**). When pentavalent-1 was considered as an entry vaccine and Pentavalent-3 as an exit vaccine, the overall dropout became 44%. Newly formed regions had the highest vaccination dropout estimate of 73% based on BCG to MCV-2 measure, followed by 70% in IDP camps according to the BCG to pentavalent-3 measure. Urban slums had the lowest dropout estimates across all measures (**Table 3**).

3.4. Determinants of vaccination dropout rate in remote and underserved settings of Ethiopia

Independent variables that were found statistically significant in the generalized estimating equation analysis at the *p*-value of ≤ 0.05 included the following: children born from mothers/caregivers who were at the lower level of the wealth quintile, caregivers who were older than 45 years, caregivers who did not have any formal education, caregivers who were working outside of their homes, caregivers who did not attend the minimum recommended number of ANC contacts (at least four times), postnatal contacts, and caregivers who did not attend a SBA during pregnancy were found to have higher dropout rates compared to their counterparts. Dropout rates were also higher for children from mothers/caregivers who were living in areas where a health facility was located very far from their homes (30 min walking distance or more). Low gender empowerment

TABLE 2 Number/proportion of children who had received various antigens according to the routine immunization schedule of Ethiopia, 2022.

Type of antigen	Number of children who had received vaccines	Percentage (%)
BCG	2,581	70.8
Penta-1	2,464	67.6
Penta-3	1,410	38.7
MCV-1	2,442	67.0
MCV-2	1,271	34.9

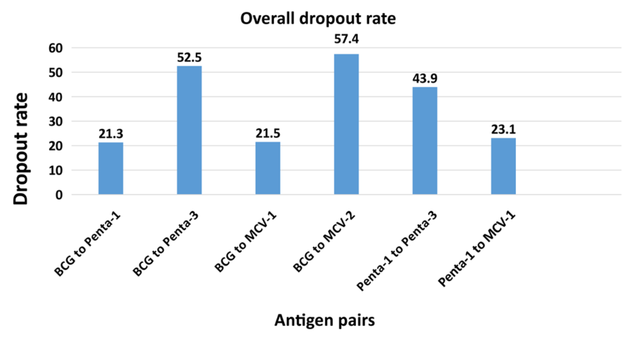

FIGURE 1
Percentage of vaccine dropout according to various measures by pair of antigens, 2022.

and a household with three or more under-five children were also contributing factors for high vaccination dropout (Table 4).

Children born from mothers/caregivers who were at the lower level of the wealth quintile had the highest dropout rates compared to their counterparts [AOR (95%CI) = 1.87 (1.38–2.52)]. Children of parents who reported not having any formal education had higher levels of dropout compared with children whose mothers/caregivers and fathers had some years of schooling [AOR (95%CI) = 1.31 (1.11–1.53)] and [AOR (95%CI) = 1.30 (1.01–1.67)], respectively.

The odds of vaccine dropout rate among children who were born from mothers/caregivers who were working at the time of the survey was nearly four times [AOR (95%CI) = 3.67 (1.24–10.86)] compared to those children who were born from mothers/caregivers who were not working. Children who were born from mothers/caregivers who had no PNC follow-up contacts were nearly two times more likely to drop out of vaccination compared to those children who were born from mothers/caregivers who had attended a PNC follow-up visit [AOR (95%CI) = 1.66 (1.15–2.39)]. In addition, the odds of childhood vaccination dropout among children who were born from mothers/caregivers who had less than four ANC contacts had a higher likelihood of dropping out of vaccination [AOR (95%CI) = 1.17 (1.00–1.82)] (Table 4).

Children who were born from mothers/caregivers who received a service from a SBA during pregnancy were less likely to drop out of vaccination compared to those children who did not get the service [AOR (95%CI) = 0.61 (0.44–0.83)]. The likelihood of vaccine dropout was twelve times higher among children who were born from mothers/caregivers that were older than 45 years at the time of the survey compared to those children who were born from mothers/caregivers that were younger than 45 years [AOR (95% CI) = 12.49 (3.87–40.33)]. The closer the mothers'/caregivers' home to the nearest health facility was also found to reduce vaccination dropout rate [AOR (95% CI) = 1.33 (1.22–1.45)]. Children of mothers who were less empowered were more likely to drop out of vaccination compared to those children of mothers who were well empowered [AOR (95%CI) = 1.63 (1.24–2.15)] (Table 4).

3.5. Vaccination dropout inequality by wealth status

Inequalities in vaccination dropout were significantly and disproportionately concentrated among the poor (CI = −0.17865141; $p < 0.01$). The negative value CI for children who dropped out of vaccination confirms pro-poor distributions (Figure 2). It was also evident from this study that Addis Ababa city administration had the highest and Gambella region had the lowest vaccination dropout inequalities by wealth (Table 5).

4. Discussion

This cross-sectional national evaluation survey aimed at estimating the prevalence of vaccine dropout rate and its

TABLE 3 Vaccination dropout estimates according to the different types of measures & target populations in remote & underserved settings of Ethiopia, 2022.

Target population group	Vaccination dropout according to various measures					
	BCG to Penta-1, *n* (%)	BCG to Penta-3, *n* (%)	BCG to MCV-1, *n* (%)	BCG to MCV-2, *n* (%)	Penta-1 to Penta-3, *n* (%)	Penta-1 to MCV-1, *n* (%)
Urban slums	20 (4.9)	55 (13.6)	44 (11.0)	171 (42.8)	46 (11.2)	41 (10.0)
Conflict affected regions	52 (24.3)	109 (51.6)	41 (19.2)	105 (49.4)	78 (38.6)	51 (25.4)
IDPs	81 (38.0)	148 (70.0)	50 (23.6)	127 (60.0)	88 (57.1)	27 (17.6)
Hard-to-reach in agrarian regions	89 (16.0)	260 (46.5)	105 (18.8)	306 (54.7)	232 (40.0)	125 (21.5)
Pastoralist population	122 (15.3)	412 (52.8)	142 (17.9)	467 (58.8)	453 (49.3)	215 (23.4)
Developing regions	179 (27.5)	449 (68.8)	130 (20.0)	394 (60.4)	336 (60.1)	158 (28.2)
Newly established regions	76 (29.9)	144 (56.7)	99 (39.0)	186 (73.1)	111 (48.8)	82 (36.0)
Refugees	50 (19.9)	139 (55.4)	83 (33.1)	174 (69.3)	99 (45.4)	73 (33.5)
All[a]	533 (21.3)	1,317 (52.5)	540 (21.5)	1,438 (57.4)	1,063 (43.9)	558 (23.1)

[a]The sum of the target population groups exceeds the total as some populations contributed to more than one domain.

TABLE 4 Generalized estimating equation model showing predictors of vaccine dropout among children aged 12–35 months in remote and underserved settings of Ethiopia, 2022.

Covariates ($n = 2,417$)	Dropout, n (%)	COR (95% CI)	AOR (95% CI)[a]
Wealth status			
Poorest	243 (59.0)	2.55 (1.82–3.58)*	1.87 (1.38–2.52)*
Poorer	252 (47.5)	1.67 (1.24–2.25)*	1.15 (0.62–2.12)
Middle	236 (44.0)	1.45 (1.16–1.81)*	1.06 (0.77–1.44)
Richer	208 (36.0)	1.04 (0.69–1.57)	0.92 (0.61–1.40)
Richest	145 (35.0)	1	1
Maternal educational status			
No formal education	699 (49.9)	1.54 (1.42–1.68)*	1.31 (1.11–1.53)*
Primary education	212 (39.1)	1	1
Secondary education	155 (34.6)	0.84 (0.53–1.33)	1.25 (0.86–1.82)
Tertiary education	18 (23.6)	0.47 (0.16–1.36)	1.04 (0.41–2.59)
Caregiver's employment status			
Working	513 (49.4)	1.52 (1.09–2.12)*	3.67 (1.24–10.86)*
Not working	570 (40)	1	1
Paternal educational status			
No formal education	538 (49.9)	1.42 (1.22–1.65)*	1.30 (1.01–1.67)*
Primary education	196 (40.7)	1	1
Secondary education	199 (38.3)	0.89 (0.71–1.13)	0.92 (0.69–1.23)
Tertiary education	45 (25.3)	0.46 (0.17–1.28)	0.61 (0.25–1.51)
Place of residence			
Urban	219 (42.6)	0.95 (0.64–1.43)	1.3 (0.96–1.78)
Rural	865 (44.3)	1	1
Child age			
12–23 months	508 (40.2)	1	1
24–35 months	575 (48.0)	1.37 (1.14–1.65)*	1.41 (1.11–1.79)*
Number of under-five children			
One	441 (36.2)	1	1
Two	557 (51.0)	1.81 (1.43–2.27)*	1.77 (1.45–2.16)*
Three or more	85 (55.4)	2.02 (0.78- 5.21)	1.89 (1.00–3.64)*
Marital status			
Not married	100 (50.1)	1	1
Married	984 (43.4)	0.76 (0.40–1.45)	1.15 (0.69–1.9)
Caregiver's age			
15–24 years	224 (38.5)	1	1
25–34 years	642 (46.8)	1.41 (1.11–1.79)*	1.27 (1.15–1.39)*
35–44 years	176 (46.9)	1.39 (1.05–1.85)*	1.35 (0.96–1.90)
45 years or above	24 (42.2)	1.16 (0.75–1.78)	12.49 (3.87–40.33)*
ANC visits			
Less than 4 contacts	637 (48.9)	1.37 (1.00–1.96)*	1.17 (1.00–1.82)*
4 or more contacts	409 (39.7)	1	1
SBA			
No	455 (52.6)	1.61 (1.23–2.08)*	1.64 (1.21–2.27)*
Yes	592 (40.3)	1	1
PNC			
No	588 (50.0)	1.57 (1.05–2.35)*	1.66 (1.15–2.39)*
Yes	459 (39.6)	1	1
Availability of health facility in the kebele			
Yes	1015 (43.1)	1	1
No	69 (61.8)	2.07 (1.13–3.80)*	1.49 (0.97–2.27)
One-way walking distance to the nearest health facility			
30 min or less	481 (39.3)	1	1
30 min or above	603 (48.6)	1.45 (1.16–1.82)*	1.33 (1.22–1.45)*
Gender empowerment			
Low	160 (60.1)	2.21 (1.68–2.93)*	1.63 (1.24–2.15)*

(*Continued*)

TABLE 4 Continued

Covariates (*n* = 2,417)	Dropout, *n* (%)	COR (95% CI)	AOR (95% CI)[a]
Medium	120 (43.3)	1.11 (0.93–1.31)	1.08 (0.97–1.21)
High	704 (40.9)	1	1
Child sex			
Boy	607 (45)	1.08 (0.89–1.29)	1.07 (0.84–1.36)
Girl	476 (42.8)	1	1
Sex of household head			
Female	120 (56.2)	1.74 (0.90–3.35)	1.88 (0.66–5.33)
Male	964 (42.8)	1	1

[a]adjusted for all variables presented in the table.
*Significant association at 5% level of significance.

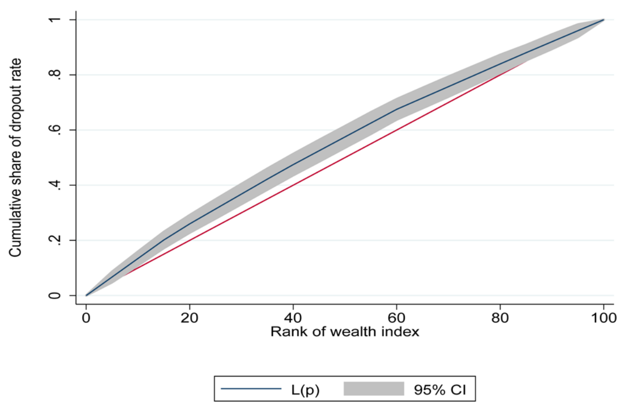

FIGURE 2
Concentration curve for vaccination dropout among children aged 12–35 months in remote and underserved settings of Ethiopia, 2022.

associated factors among children aged 12–35 months in remote and underserved areas of Ethiopia. It is the first extensive national study on immunization after the two great challenges (COVID-19 and internal conflicts) Ethiopia has recently experienced.

In the immunization program, the first and third doses of Pentavalent vaccine are referred to as tracer indicators (1, 24). In this study, apart from the Pentavalent vaccine, other antigens were also used to estimate vaccination dropout. Overall dropout as well as dropout disaggregated by different population domains were performed. In addition, contributing factors for vaccination dropout and inequality of dropout based on wealth status were also explored using generalized estimating equation and concentration curve/index, respectively.

TABLE 5 Vaccination dropout inequality by wealth status in regions, 2022.

Region	N	Mean	Margin
Afar	355	−0.2934411	1
Amhara	288	−0.118632	0.0570416
Oromia	309	−0.2033019	0.0152045
Somali	216	−0.2034953	0.2036885
Benishangul Gumuz	153	−0.2794761	0.0040176
SNNPR	239	−0.1845429	0.0989508
Sidama	141	0.0930139	0.0843412
Southwest	121	−0.1628358	0.1206579
Gambella	366	−0.03338	0.2458167
Harari	43	−0.4165674	−0.1330737
Addis Ababa	181	−0.869686	−0.5861923
Diredawa	52	−0.245111	0.0383828
Total	2,464	−.1772053	–

The magnitude of vaccination dropout ranged from 21.3% based on BCG to Penta-1 to 57.4% based on BCG to MCV-2. Using Penta-1 to Penta-3 measures, vaccination dropout was 44%. All the dropout estimates in our study were higher compared to the maximum tolerable dropout level of 10% by the WHO. This might be indicative of poor performance of immunization programs in underserved settings of Ethiopia. Vaccination dropout estimates of the present study in the pastoralist population of Ethiopia were higher compared to dropout estimates from a previous study conducted in the same study settings in Ethiopia. In this study, dropout rates using penta-1 to Penta-3 was 49.3% and Penta-1 to MCV-1 was 23.4% which are much higher than dropout estimates of a previous study done in the same study setting using same pairs of antigens, which found rates of 22.1% and 9.0%, respectively (8). In addition, dropout estimates of the present study were higher compared to a dropout estimate of another study (33.1%; Penta-1 to Penta-3) conducted in Jigjiga district, Somali regional state of Ethiopia (28). The dropout rate in this study (44%) was also higher than 15% as reported in the mini demographic and health survey 2019 (Penta-1 to Penta-3) (29). The higher dropout rates in the present study might be attributed to the COVID-19 pandemic and internal conflicts.

Globally, childhood vaccination is influenced by parental education (30, 31). Our study has shown that children born from mothers/caregivers and fathers who reported not attending any formal education had higher levels of dropout compared with their counterparts and, respectively. This is consistent with studies conducted in Nepal, Kenya, Uganda, Guinea Bissau, Ethiopia, Nigeria, and Benin where children of uneducated mothers and fathers reported to have a higher vaccination dropout (32–38). Previous studies from rural India and rural Mozambique also reported that children whose mothers had no schooling were more likely to drop out of vaccination compared with children whose mothers had some years of schooling (39–41). Moreover, our study indicated that children of working mothers/caregivers had a higher likelihood of being dropped out from vaccination programs compared to their counterparts. This is also in line with a study done in Nepal. This might be due to the fact that working mothers have little time to stay with and care for their children (32).

Our study also showed the inverse relationship between wealth status and vaccination dropout. Children born from mothers/caregivers who were at the lower level of the wealth quintile had the highest dropout compared to their counterparts. This is supported by studies conducted in Pakistan (42), Kenya (31), and Nigeria (37). However, a study from Nepal by Thapa et al. contradicts with our finding that stated that children from middle and rich families reported a higher dropout (32).

The 2016 ANC model of WHO recommends a minimum of eight ANC contacts throughout pregnancy (43). Our study showed that mothers who had fewer than four or no ANC visits and those who did not seek help from SBAs showed higher dropout rates than others. This might be because ANC contacts provide information about childbirth, newborn care, vaccinations, and the growth of children. In other words, inadequate ANC visits, late visits, or fewer than the recommended number of visits have been correlated with poor newborn health. This finding is supported by other studies conducted in Ethiopia, Nepal, Benin, and 69 low- and middle-income countries (13, 32, 38, 44).

Children who were born from mothers/caregivers who had no PNC follow up contacts were nearly two times more likely to drop out of vaccination compared to those children who were born from mothers/caregivers who had attended PNC follow-up visits. This finding aligns with a study conducted in North Gondar zone and Laelay Adiabo districts of Ethiopia and a study from Benin which concluded that the likelihood of defaulting from completion of child vaccination was higher among mothers/caregivers who did not attend PNC after birth as compared to those attended at least once (1, 38, 45). In addition, our results are also consistent with studies conducted in Kenya and Cameroon which showed that failure to attend PNC was a barrier to complete vaccination. The possible explanation of this might be missed opportunity to get advice on the benefits of child vaccination that ultimately leads mothers/caregivers to drop out of child vaccination (46, 47).

In our study, distance to the health facility was found to contribute to vaccination dropout. Closer distance from the mothers'/caregivers' homes to a health facility correlated with lower vaccination dropout rates. This is consistent with findings from Nigeria, Ethiopia, Kenya, Cameroon, and Mozambique (13, 33, 47–51). The study from Kenya showed that residing over 5 km away from a health facility was associated with higher odds of dropping out. Lack of access to health facilities in the neighborhood was also found to contribute to high vaccination dropout. This aligns with results from a community-based participatory research study conducted in Mozambique which found that vaccination dropout was related to a lack of access to healthcare facilities (12, 40).

The present study has shown that the wealth status of mothers/caregivers contributed to vaccination dropout inequality by wealth status. Inequalities in vaccination dropout were disproportionately concentrated among the poor. The negative value (CCI = −0.17865141) for children who dropped out of vaccination confirms pro-poor distributions. Addis Ababa city administration and Gambella region have the highest and the lowest inequality of vaccination dropout by wealth, respectively. However, this does not mean that Addis Ababa city administration and Gambella have the highest and lowest dropout rates. Although vaccinations are provided free-of-charge in Ethiopia, there are indirect costs that mothers/caregivers are required to pay (for instance, transportation costs) which often limits the uptake of maternal and child health services, including vaccination. In this regard, mothers/caregivers at the lower level of the wealth category are more exposed to such challenges in accessing healthcare facilities, which ultimately leads to vaccination dropout. Our finding is consistent with studies conducted in Nigeria, Benin, and the Democratic Republic of the Congo. Using a nationally representative data, Ataguba et al. stated that existing immunization coverage disparities disproportionately benefited the rich (37, 38, 52, 53).

Maternal age was significantly associated with vaccination dropout in the present study. The likelihood of vaccine dropout was twelve times higher among children who were born from mothers/caregivers that were older than 45 years at the time of the survey compared to those children who were born from mothers/caregivers that were younger than 45 years. This is in line with a previous study conducted in Ethiopia (41). It was evident from this study that the odds of vaccination dropout in children from women with low levels of empowerment was 1.63 higher compared to children from women with high levels of empowerment. This aligns with studies conducted in Mozambique and the Democratic Republic of the Congo (51, 53).

This study had several strengths worth mentioning. Although study settings included areas where there were active conflicts, the study team still managed to collect data in those areas. Ascertainment of child vaccination dropout was based on information gathered from multiple sources. Vaccination cards, medical records, and maternal recall were used to ascertain vaccination dropout. This triangulation helped to verify and validate the results. The use of digital applications and experienced data collectors helped to ensure high-quality data was gathered. The results from this study could be used as a baseline to reduce vaccination dropout in underserved settings of Ethiopia.

The study also had some limitations, including difficulty to make a causal inference and susceptibility to biases such as nonresponse bias and recall bias which are directly linked to the study design i.e., cross-sectional. Mothers/caregivers who did not possess EPI cards might forget the vaccination status of their children and this ultimately might lead to misclassification.

5. Conclusion and recommendations

Vaccination dropout estimates were high among children residing in remote, underserved, and conflict affected settings of Ethiopia. Poor wealth quintile, uneducated parents, advanced maternal age, low women empowerment, inaccessibility of health facilities, and limited utilization of maternity care services were found to contribute to vaccination dropout.

Strengthening horizonal integration of immunization services with maternal & child health services such as antenatal and postnatal cares, sick childcare, nutritional screening, growth monitoring, oral rehydration therapy training sessions, vitamin A supplementation and family planning will reduce the number of children who are eligible for vaccination but do not receive one or more of the vaccine doses i.e., missed opportunities for vaccination. Empowering women is also another vehicle to reduce vaccination dropout. Strengthening outreach campaigns, supplementary immunization activities (SIAs), Periodic Intensification of Routine Immunization (PIRI) in remote and underserved areas will help reduce vaccination dropout. Policy makers in Ethiopia need to address the disproportionate concentration of vaccination dropout among the poor by strengthening women's utilization of healthcare services and the accessibility of health facilities in rural kebeles.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The research was carried out in accordance with national and international ethical guidelines. The research protocol was reviewed and approved by the institutional review board of the Ethiopian Public Health Institute (416/2021). Information was collected after receiving written consent from the caretakers. To maximize beneficence, all children who did not receive any vaccine were referred to the nearest health facility using a referral form.

Author contributions

FS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. SG: Supervision, Writing – review and editing. GA: Supervision, Writing – review and editing. DT: Funding acquisition, Resources, Writing – review and editing. WA: Funding acquisition, Resources, Writing – review and editing. LM: Writing – review and editing. TW: Writing – review and editing. TF: Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Paper II

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Decomposition Analysis of Socioeconomic Inequalities in Vaccination Dropout in Remote and Underserved Settings in Ethiopia

Fisseha Shiferie,[1,2]* Samson Gebremedhin,[3] Gashaw Andargie,[1] Dawit A. Tsegaye,[1] Wondwossen A. Alemayehu,[4] and Teferi Gedif Fenta[2]

[1]*Project HOPE Ethiopia Country Office, Addis Ababa, Ethiopia;* [2]*School of Pharmacy, Addis Ababa University, Addis Ababa, Ethiopia;* [3]*School of Public Health, Addis Ababa University, Addis Ababa, Ethiopia;* [4]*Project HOPE Headquarters, Washington, District of Columbia*

Abstract. Despite increments in immunization coverage over the past decades, substantial inequality due to wealth status has persisted in Ethiopia. This study aimed to decompose the concentration index into the contributions of individual factors to socioeconomic inequalities of childhood vaccination dropout in remote and underserved settings in Ethiopia by using a decomposition approach. A wealth index was developed by reducing 41 variables related to women's household living standards into nine factors by using principal component analysis. The components were further totaled into a composite score and divided into five quintiles (poorest, poorer, middle, richer, and richest). Vaccination dropout was calculated as the proportion of children who did not get the pentavalent-3 vaccine among those who received the pentavalent-1 vaccine. The concentration index was used to estimate socioeconomic inequalities in childhood vaccination dropout, which was then decomposed to examine the factors contributing to socioeconomic inequalities in vaccination dropout. The overall concentration index was −0.179 ($P < 0.01$), confirming the concentration of vaccination dropout among the lowest wealth strata. The decomposition analyses showed that wealth index significantly contributed to inequalities in vaccination dropout (49.7%). Place of residence also explained −16.2% of the inequality. Skilled birth attendance and availability of a health facility in the kebele (the lowest administrative government structure) also significantly contributed (33.6% and 12.6%, respectively) to inequalities in vaccination dropout. Wealth index, place of residence, skilled birth attendance, and availability of a health facility in the kebele largely contributed to the concentration of vaccination dropout among the lowest wealth strata. Policymakers should address vaccination inequality by designing more effective strategies.

INTRODUCTION

In spite of the remarkable global improvement in basic vaccination coverage, there are inequalities in access to childhood vaccination within and between countries. Within countries, child vaccination data showed that richer subgroups tend to have higher coverage, whereas the coverage among poorer subgroups varied across countries.[1] For example, studies in India,[2] Nigeria,[3] and Brazil[4] indicated that children of mothers who had higher education levels and household wealth status were more likely to have high vaccination coverage. Studies from low- and middle-income countries suggested that immunization coverage is pro-rich in most countries. Gambia, Namibia, and Kyrgyz Republic were the only countries where children who belonged to higher socioeconomic status group were less likely than their lower socioeconomic status counterparts to receive all four core vaccines.[5,6]

Despite the steady increments in immunization coverage over the past decades, pro-urban, pro-rich, and pro-educated inequalities in vaccination coverage have been observed in sub-Saharan African countries.[7–9] West African countries such as Guinea, Mali, and Nigeria had the widest equity gaps in immunization, with inequalities in coverages and dropouts mostly related to poverty, low maternal education, and living in certain disadvantaged subnational regions. In these countries, inequalities in bacillus Calmette-Guérin (BCG) and diphtheria, tetanus, and pertussis three (DTP3) coverage and dropouts were greater than 20 percentage points between the wealthiest and the poorest, between high-coverage regions and low-coverage regions, and between children of mothers with at least secondary education and those with no formal education. Place of residence contributed minimally to the inequality in coverage and dropout.[10] A study conducted in 24 countries in the African region revealed that the difference in vaccination dropout estimates between the highest and lowest quintiles was 14.9% or more. These inequalities in dropout rate stemmed from lower estimated national immunization coverages.[11]

According to the Ethiopian Demographic and Health Surveys (DHS) of 2011 and 2016, the uptake of BCG, DTP3, oral polio vaccine three (OPV3), and measles vaccines was disproportionately concentrated among children from wealthy households. For example, in 2016, DTP3 had a concentration index (CnI) of 0.175. The estimate for the distribution of children who received no vaccination increased from a CnI of −0.092 in 2011 to a CnI of −0.184 in 2016. The negative values for children who received no vaccination confirms pro-poor distributions. The decomposition results showed that the significant contributors to socioeconomic inequality in basic vaccination status included wealth index, maternal education, contraceptive use, antenatal care (ANC) contacts, exposure to media, and place of residence. The use of maternal health services had the highest significant contributions to socioeconomic inequalities in child vaccination. Antenatal care contacts had a 45.4% contribution in 2011 and a 50.4% contribution in 2016. Wealth status is the other significant contributor, 23.9% in 2011 and 21.2% in 2016. On the other hand, rural residence had a negative contribution to socioeconomic inequalities in child vaccination in both surveys.[12–14]

Although the establishment of more community-level service delivery points over the last two decades and the provision of free vaccination services at public health facilities improved childhood vaccination coverage, substantial inequality due to wealth status has persisted in Ethiopia.[15–17] Another

* Address correspondence to Fisseha Shiferie, Project HOPE Ethiopia Country Office, P.O.Box 45, Addis Ababa, Ethiopia. E-mail: fshiferie21@gmail.com

study conducted in Ethiopia indicated the presence of persistent socioeconomic inequalities in terms of vaccine uptake. Children from the poorest households lagged behind those from relatively wealthy households in vaccination. A decomposition analysis of socioeconomic inequalities revealed that maternal educational level, ANC use, institutional delivery, and exposure to media consistently contributed to the inequality observed in vaccine uptake.[18]

Many studies in Ethiopia have assessed vaccination coverage, predictors associated with vaccination coverage, and socioeconomic inequalities in vaccination coverage. However, there has been no study that attempted the decomposition of socioeconomic inequalities in vaccination dropout especially in remote and underserved settings (including pastoralist regions, developing regions, newly established regions, conflict-affected areas, underserved urban populations, internally displaced populations [IDPs], and refugee populations) of Ethiopia. Hence, the objective of this study was to decompose the CnI into the contributions of individual factors to socioeconomic inequalities of childhood vaccination dropout by using a decomposition approach.

MATERIALS AND METHODS

Study design and settings. This study was part of a cross-sectional national evaluation survey that was conducted from May to July 2022. Prior to the quantitative survey, zero-dose and underimmunized areas were identified through qualitative situational and geospatial analyses based on secondary data sources. The study was conducted by following a single-round, cross-sectional survey design.

In line with the understanding that nearly half of zero-dose and under-immunized children in low-income countries are from hard-to-reach communities, conflict-affected settings, or disadvantaged urban areas,[19] this study targeted populations in the following eight partly overlapping settings:

1. Pastoralist regions and populations: Afar and Somali regions and specific pastoralist or semipastoralist settings in Oromia, Southern Nations, Nationalities, and Peoples (SNNP), Southwest Ethiopia Peoples, and Gambella regions.
2. Developing regions: Afar, Somali, Gambella, and Benishangul Gumuz regions.
3. Newly established regions: Sidama and Southwest Ethiopia Peoples regions.
4. Conflict-affected areas: selected settings in Afar, Amhara, Oromia, and Benishangul Gumuz regions.
5. Underserved urban populations: urban slums in six selected cities (Addis Ababa, Bahirdar, Hawassa, Dire Dawa, Harar, and Adama) and rural areas under Dire Dawa City administration and the Harari region.
6. Hard-to-reach areas in major regions: selected remote districts in the Amhara, Oromia, and SNNP regions.
7. Internally displaced persons: selected IDP centers in the Afar, Amhara, Oromia, and Benishangul Gumuz regions.
8. Refugees: refugees from selected camps in the Somali, Afar, and Gambella regions.[20,21]

Study participants. The target population was children under 5 years old who resided in underserved, remote, and conflict-affected areas of Ethiopia. All children aged 12 to 35 months were included as study participants.

Sample size determination. The sampling design of the study was adopted from WHO's 2018 *Vaccination Coverage Cluster Surveys* manual.[22] The adequate sample size for each of the target populations was calculated using Cochran's single proportion sample size formula,[23] assuming 95% confidence level, 4% margin of error, 16% prevalence of zero-dose children,[13] and 10% compensation for possible nonresponse. The following sample size formula was used to calculate the number of children required in a prevalence study: $n = \frac{Z2p(1-p)}{d2}$, where n is the total sample size needed, Z is the statistic corresponding to the 95% confidence level, which is 1.96, p is the prevalence of zero-dose children in previous studies in Ethiopia, and d is precision (corresponding to effect size).[24] Therefore, a sample size of 360 was required for each of the aforementioned target population domains.

According to the Ethiopian DHS 2016 and Mini DHS 2019 data, an average of 12 children aged 12 to 35 months of age are available per enumeration area (EA).[13,25] Therefore, for each of the population domains, a minimum of 30 EAs were required to recruit 360 children in each target population, assuming all children in the EA would be eligible for inclusion in the study. In urban slums, 40 EAs were randomly selected, and 480 children were selected (Table 1).[20,21]

Initially, it was planned to include 4,080 children from 340 EAs (a minimum of 360 sample per population domain) in the survey. However, in the actual survey, 3,646 children aged 12 to 35 months from 340 EAs were enrolled because of conflict in some of the study districts. The total sample size was large enough to allow subgroup inequality analysis based on sex, age, and other pertinent background characteristics, including socioeconomic status.[20,21]

Sampling procedure. Children aged 12 to 35 months were selected using a cluster sampling approach in a two-step procedure. First, EAs were randomly selected from the total EAs available in each target population domain.[20,21] In this case, the EAs delineated by the Central Statistical Agency of Ethiopia for the recent census were used as a sampling frame.[13] In the case of urban slums, hotspot urban slums in Addis Ababa, Adama, Bahir Dar, Hawassa, Harar, and Dire Dawa cities were located and delineated, and EA maps were drawn by experienced cartographers. In the case of IDP and refugee camps, villages or clusters were considered EAs.

TABLE 1
Total sample size and EAs required for the vaccination coverage survey, Ethiopia, 2022

Types of Study Population	Number of EAs	Total Sample Size (Number of Children)
Pastoralist areas in Oromia, SNNP, and Southwest Ethiopia Peoples regions	30	360
Hard-to-reach areas	30	360
Conflict-affected areas	30	360
Refugees	30	360
IDPs	30	360
Newly formed regions: Sidama and Southwest Ethiopia Peoples regions	30	360
Urban slums	40	480
Afar	30	360
Somali	30	360
Benishangul Gumuz	30	360
Gambella	30	360
Total	340	4,080

EAs = enumeration areas; IDPs = internally displaced persons; SNNP = Southern Nations, Nationalities, and Peoples.

Second, all eligible children in each EA were listed, and 12 children were ultimately selected using a smartphone-based random-number generator.[20,21]

Data collection procedures and data quality assurance. Data were collected using pretested tools prepared in five local languages (Amharic, Afan Oromo, Somali, Afar, and Sidama). Survey data were collected by 48 experienced enumerators and 24 supervisors using the CommCare digital app, an open-source and user-friendly application system which is interoperable with major data analytics and visualization software. The app helped to collect individual child-level and household information to ensure high-quality data collection, cleaning, and monitoring in real time.[20,21]

Enumerators and supervisors were recruited based on educational status (at least diploma holders in a health-related discipline), previous experience in similar national surveys, and familiarity with the CommCare digital app.[21] Prior to deployment, the enumerators and supervisors received a 5-day training guided by a structured training manual. The training included an explanation of the sampling approach, basic principles of data collection, line-by-line discussion on the questionnaire, an overview on using the CommCare digital app, mock interviews, field practice, and a review of basic ethical practices of research involving human participants.[20]

Data collectors were allowed to collect data from up to six individuals per person per day. To validate the quality of the data, one-third of all the study participants were reinterviewed by the supervisors. The uploaded data were closely monitored by the research team throughout the survey implementation period.[20]

Ascertainment of childhood vaccination. The vaccination status of children was ascertained based on three different sources of information, including caregiver reports, home-based (vaccination card) reports, and facility-based reports, as recommended by the WHO. In areas where the mother or caregiver presented an immunization card, the child's immunization status was based on vaccination card review. Where an immunization card was not available, the immunization status was assessed according to mothers'/caregivers' self-reports/recalls. Facility-based reports were considered in determining vaccination status when a mother/caregiver reported that her child was vaccinated but a vaccination card was not available. In this case, data collectors were expected to visit the nearby health facility to verify mother's/caregiver's self-report/recall based on the available medical record. Previous studies have proven this to be a reliable method to ascertain childhood vaccination in resource-limited settings with poor documentation of childhood immunization.[21,26]

Variables of the study. Vaccination dropout is the proportion of children who did not receive the subsequent vaccine among those who received the first vaccine. It was calculated as the proportion of children who did not receive the pentavalent-3 vaccine (the third dose that is given to a child at 14 weeks of age) among those who received the pentavalent-1 vaccine (the first dose that is given at 6 weeks of age). The predictor variables of vaccination dropout include wealth index, marital status, child age, respondent age, time to walk to the health facility (one way), maternal educational status, paternal educational status, caregiver's employment status, ANC visits, postnatal care (PNC) services, place of residence, number of children under 5 years of age, skilled birth attendance (SBA), availability of a health facility in the kebele (the lowest administrative government structure), gender empowerment, child sex, and sex of the household head.[21]

Gender empowerment is a composite index measuring gender inequality in economic participation, decision-making mainly on health-related matters, and power over economic resources. Gender empowerment was measured using a composite scale (minimum = 0, maximum = 6). Women's reported power based on six components (major household purchases, expending own income, expending partner's income, visiting families/relatives, and deciding on health care for herself and the index child) was used to develop the scale. Each component was coded as "1" when the decision was made by the woman or jointly with her partner and "0" when the decision was made solely by the partner. Finally, a score out of 6 was computed and categorized into low (0–2), medium (3 or 4), or high (5 or 6) ordinal categories.[20,21]

Wealth index is a composite variable that measures the woman's household living standards. At the design stage, a representative mix of variables considering the contexts of urban and rural communities was carefully selected. Wealth index was computed as a composite index of living standard as recommended by the DHS program. It was developed based on ownership of valuable assets and livestock, size of land for agriculture and housing purposes, materials used for house construction, and access to basic social services, including electricity, banking, improved water sources, and body waste disposal methods. A total of 41 variables were reduced into nine factors using principal component analysis. The components were further totaled into a score and ultimately divided into five quintiles (poorest, poorer, middle, richer, and richest).[13,20,21]

STATISTICAL ANALYSES

Data were collected using the CommCare digital app[27] and stored in a local server on a daily basis. It was exported to STATA version 17.0[28] for advanced statistical analysis. To balance weighted and unweighted sample sizes, linearization of poststratification weights were made.[21]

The outcome variable was whether a child had dropped out of the third dose of the pentavalent vaccine. Predictor variables considered in the current study were selected based on proven relationships and predicting factors from published literature and their biological plausibility. These included wealth status, marital status, child age, respondent age, time to walk to health facility (one way), maternal educational status, caregiver's employment status, ANC visits, PNC services, place of residence, number of children under 5 years of age, SBA, availability of a health facility in the kebele, gender empowerment, child sex, and sex of the household head.[20,21]

Vaccination dropout inequality by wealth status. Vaccination dropout inequality by wealth status was estimated using the CnI. The CnI is described as two times the area between the line of equality and the concentration curve. The index takes a value between -1 and $+1$; an index of 0 indicates the presence of equality in the uptake of vaccines. If wealth-related inequalities exist, it can be seen in one of two forms. The first is when there is uneven concentration of dropout among the rich, and, in this case, the CnI takes on a positive value. The second is negative-value CnI, which implies a high concentration of vaccination dropout among the poor. The greater the magnitude of inequality, the wider the gap will be between the line of equality and the CnI.[14,21]

The CnI can then be measured as follows: twice the covariance of the health variable and the ranking of the living standards variable r all divided by the mean of the health measure (μ). Greater absolute CnI values indicate greater inequality in vaccination dropout.

$$CnI = \frac{2}{\mu} cov\ (h, r) \tag{1}$$

This study makes use of the Erreygers corrected CnI, which is algebraically expressed as shown below.

$$E(h) = \frac{4\mu}{b - a} CnI \tag{2}$$

Where μ is the mean of the health variable (vaccination dropout), *CnI* is the standard CnI, with *b* and *a* representing the upper and lower bounds of the outcome variable (*h*). In our study, the range *b–a* is unity, as the outcome variable is binary.[29]

Decomposing socioeconomic inequality of vaccination dropout. The values of CnI show and quantify the level of inequalities related to wealth in the use of health services. However, it does not highlight the pathways through which inequality occurs. Policymakers are also interested in the factors that contribute to wealth-related inequalities in vaccination dropout. The CnI of a health variable can be decomposed into the contributions of individual factors to the overall level of wealth-related inequalities in childhood vaccination dropout. This can be done using an approach developed by Wagstaff et al.[30]

Our health variable *hi* (vaccination dropout) is linked to a set of explanatory variable *Xij* by the following linear model.

$$hi = \alpha + \sum_{j=1}^{q} (\beta j Xj) + \varepsilon \mathrm{i} \tag{3}$$

If we have a linear model such as that shown in Equation (3), Wagstaff et al. show that the CnI for *hi* can be written as:

$$CnI\ (h) = \sum_{j=1}^{q} \frac{(\beta j x \overline{x} j)}{\mu h} CnI\ (Xj) + \frac{GC\varepsilon}{\mu h} \tag{4}$$

In Equation (4), *CnI (h)* is the CnI for the health variable *h* (vaccination dropout), $\overline{x}j$ is the mean of *xj*, μh is the mean of the health variable, *CnI(xj)* is the CnI for *xj,* and $GC\varepsilon$ is the generalized CnI for the error term. In this equation, the first part is the weighted sum of the CnI for the variable *xj*. The weight of each regressor is determined by the elasticity ($\beta\overline{x}j$) of *h* with respect to *xj*. The second part of the equation is the residual socioeconomic inequalities in health that cannot be explained by the CnI of the regressors. Since we applied the Erreygers normalization to the calculation of the CnI for the socioeconomic inequalities in vaccination dropout, the corrected CnI for the health variable is formulated as:

$$E\ (h) = 4 \sum_{j=1}^{q} \beta j Xj CnI\ (Xj) + 4GC\varepsilon \tag{5}$$

Equation (5) can now be used to decompose socioeconomic inequalities in vaccination dropout, showing the contribution of each factor. If the contribution of variable *x* is positive, then inequality in the health variable would decrease if variable *x* becomes equally distributed across the socioeconomic group, ceteris paribus. The opposite is also true, i.e., if a contribution is negative, the absence of inequalities in that variable would result in an increase in inequality, ceteris paribus. The absolute contribution a variable makes to socioeconomic inequality is a product of the elasticity ($\beta\overline{x}j$) of vaccination dropout for each variable and the CnI for each variable. Therefore, to estimate the contribution, we need to first estimate the coefficients of the explanatory variables via a regression. Ordinary least squares, probit, and generalized linear models are the three most common regression methods used for decomposition of inequalities.[30,31] The generalized linear model for decomposition of the Erreygers CnI was used in this study. A bootstrapping technique was used to generate the standard errors for the absolute contributions. Data analysis was conducted in STATA 17, and poststratification sample weights were used in all analyses to adjust for unequal probabilities of selection and nonresponse.[21]

Ethical approval and consent to participate in the study. The research was implemented in compliance with national and international ethical principles. The research protocol was reviewed and approved by the institutional review board of the Ethiopian Public Health Institute (416/2021). Information was collected after receiving written informed consent from the caretakers. To maximize beneficence, all zero-dose children were referred to the nearest health facility using a referral form.

RESULTS

Sociodemographic characteristics. A total of 3,646 mothers/caregivers with children aged 12 to 35 months participated in the study with a response rate of 97.7%. Over half of (54%) respondents were between 25 and 34 years of age, and the majority of them (59.2%) had no formal education. More than 81% of respondents were from rural areas, and 17% of them were from the Afar region. Nearly 91% of the respondents were married/living together, and 57% were unemployed at the time of the survey (Table 2).[21]

Vaccination dropout. Vaccination dropout was calculated using Pentavalent-1 and Pentavalent-3 vaccines. The overall vaccination dropout estimate was 44%. While urban slums had the lowest dropout estimate (11.2%), the highest dropout estimate was from developing regions (60.1%), followed by IDPs (57.1%) (Table 3).

Vaccination dropout inequality by wealth status. Vaccination dropout by wealth status was also estimated. Children born from mothers/caregivers who were at the lower level of the wealth quintile had the highest dropout rates in comparison with their richest counterparts (59% versus 35%) (Table 4).

The statistically significant negative value of the CnI (-0.179; $P < 0.01$) in Table 5 confirms the concentration of vaccination dropout among the lowest wealth strata.[21]

Decomposing socioeconomic inequality of vaccination dropout. Before the decomposition analysis was carried out, the multicollinearity among predictor variables was assessed using the variance inflation factor (VIF). The VIF ranged from 1.01 to 2.17, which implied that multicollinearity does not exist among these variables. Several published articles showed that wealth index is a major determinant that influences socioeconomic

TABLE 2
Sociodemographic characteristics of respondents and children in underserved settings of Ethiopia, 2022

Characteristics	Frequency (Number of Respondents or Children)	Percent
Child's sex		
Male	1,985	54.4
Female	1,661	45.6
Child's age (months)		
12–23	1,849	50.7
24–35	1,797	49.3
Respondent's age (years)		
15–24	875	24.0
25–34	1,969	54.0
35–44	572	15.7
≥45	104	2.9
Do not know	126	3.5
Respondent's educational status		
No formal education or preschool	2,158	59.2
Primary education	788	21.6
Secondary education	616	16.9
Tertiary education	84	2.3
Marital status		
Not ever married	43	1.2
Married/living together	3,312	90.8
Separated	83	2.3
Divorced	110	3.0
Widowed	98	2.7
Place of residence		
Urban	677	18.6
Rural	2,969	81.4
Caregiver's employment status		
Unemployed	2,098	57.6
Employed	1,548	42.4
Region*		
Afar	636	17.4
Amhara	372	10.2
Oromia	431	11.8
Somali	480	13.2
Benishangul Gumuz	216	5.9
Southern Nations, Nationalities, and Peoples	300	8.2
Sidama	239	6.6
Southwest Ethiopia Peoples	181	5.0
Gambella	479	13.1
Harari	60	1.6
Addis Ababa	192	5.3
Dire Dawa	60	1.6
Household size (no. of people)		
2–5	2,044	56.0
≥6	1,602	44.0

* Unweighted sample size.

inequality. Hence, we included wealth index as a predictor variable to quantify the magnitude of wealth-related inequalities in vaccination dropout. Presented in the first column of Table 6 are CnIs of predictor variables. This column provides insights

TABLE 3
Pentavalent-1 to pentavalent-3 vaccination dropout across different remote and underserved population groups of Ethiopia, 2022

Population Group	Pentavalent-1 to Pentavalent-3 Dropout, % (95% CI)
Urban slums	11.2 (8.3–14.7)
Conflict-affected regions	38.6 (32.0–45.9)
IDPs	57.1 (48.9–65.1)
Hard-to-reach in agrarian regions	40.0 (36.1–44.2)
Pastoralist population	49.3 (46.0–52.6)
Developing regions	60.1 (55.9–64.2)
Newly formed regions	48.8 (42.0–55.4)
Refugees	45.4 (38.7–52.3)
All	44.0 (41.9–45.9)

IDPs = internally displaced persons.

TABLE 4
Dropout rate across the five wealth groups in remote and underserved population groups of Ethiopia, 2022

Wealth Status	Dropout Rate, %
Poorest	59.0
Poorer	47.5
Middle	44.0
Richer	36.0
Richest	35.0

into the distributions of vaccination dropout among the different wealth quintiles and the socioeconomic determinants. The CnI for children from the lowest wealth strata was negative, which indicated that childhood vaccination dropout was concentrated among the relatively poorer families. Furthermore, mothers who had lower educational status, who were residing in rural areas, who were living in areas where it took over 30 minutes to get to the nearest health facility, who were less gender empowered, who had two or more children under 5 years old, and who were in the age range of 25 to 34 years had a negative CnI value, indicating that these variables were concentrated among people of lower socioeconomic (poorer) status.

Estimated marginal effects from the regression analysis are presented in the third column of Table 4. The marginal effects indicated the association between the predictor variables and outcome indicator. Wealth index, maternal educational status, respondent age, time to walk to the nearest health facility, caregivers' employment status, ANC, PNC, SBA, women's empowerment, number of children under 5 years old, and child age were significantly associated with vaccination dropout (Table 6).

Table 6 also summarizes the percentage contributions of the predictor variables to socioeconomic-related inequalities in vaccination dropout. Predictor variables that contributed the most to socioeconomic inequalities in vaccination dropout were place of residence (urban or rural), wealth index, SBA, and availability of a health facility in the kebele. The absolute values of the percentage contributions of predictors indicated the magnitude of their contributions to inequality. A positive value for a percentage contribution indicates that the predictor increases the inequality, and the opposite is true for a negative value. Our study showed that wealth index is a significant contributor to inequalities in vaccination dropout (49.7%). Place of residence also explained −16.2% of the inequality in vaccination dropout. SBA and availability of health facility in the kebele were also large contributors to inequality, contributing 33.6% and 12.6% to inequalities in vaccination dropout, respectively.

The negative contribution by place of residence indicated that if place of residence was equally distributed across the wealth index, then inequalities in vaccination dropout would increase by 16.2%. On the other hand, the positive contribution by SBA indicated that if SBA was equally distributed across the

TABLE 5
Concentration index and standard error for the outcome variable

Index	No. of Observations	Index Value	Standard Error	*P*-Value
Erreygers normalized CnI	2,464	−0.17865141	0.02232006	0.0000

CnI = concentration index.

TABLE 6
Decomposition of socioeconomic inequalities in vaccination dropout in remote and underserved settings of Ethiopia, 2022 (N = 2,417)

Variables (N = 2,417)	CnI	Elasticity	Margins	% Contribution	Total % Contribution
Wealth status					
Poorest (ref.)					
Poorer	−0.39*	−0.09*	−0.11*	−20.8*	
Middle	−0.02	−0.10	−0.12*	−1.0	
Richer	0.40*	−0.16*	−0.17*	35.8*	
Richest	0.56*	−0.11*	−0.17*	35.7*	49.7
Maternal educational status					
No formal education (ref.)					
Primary education	−0.01	−0.04	−0.04	−0.1	
Secondary education	0.22*	−0.01*	−0.01	0.8*	
Tertiary education	0.08*	−0.02*	−0.18*	1.0*	1.7
Caregiver’s employment status					
Working	0.06†	0.15†	0.09*	−4.8†	−4.8
Not working (ref.)					
Place of residence					
Urban (ref.)					
Rural	−0.19*	−0.14*	−0.05	−16.2*	−16.2
Child age (months)					
12–23 (ref.)					
24–35	0.03	0.14	0.07*	−2.4	−2.4
Number of children under 5 years old					
1 (ref.)					
2	−0.09*	0.19*	0.11*	9.0*	
≥3	−0.03†	0.03†	0.10†	0.4†	9.4
Marital status					
Not married (ref.)					
Married	0.03*	0.012*	0.03	2.3*	2.3
Respondent age (years)					
15–24 (ref.)					
25–34	−0.05†	0.14†	0.06*	3.8†	
35-44	0.04†	0.04†	0.06†	−0.9†	
≥45	0.01	0.05	0.49*	−0.0	2.9
ANC contacts					
<4 (ref.)					
≥4	0.13*	−0.08*	−0.05†	5.7*	5.7
SBA					
No (ref.)					
Yes	0.23*	−0.26*	−0.11*	33.6*	33.6
PNC contacts					
No (ref.)					
Yes	−0.01	0.21	0.10*	0.8	0.8
Availability of health facility in the kebele					
Yes	0.07*	−0.31*	−0.08	12.6*	12.6
No (ref.)					
One-way walking distance to the nearest health facility (minutes)					
≤30 (ref.)					
>30	−0.11*	0.14*	0.07*	8.4*	8.4
Gender empowerment					
Not married (ref.)					
Low	−0.05*	0.05*	0.12*	1.3*	
Medium	0.01	0.01	0.01	−0.0	
High	0.07*	0.0*	0.0	0.0*	1.3
Child sex					
Male (ref.)					
Female	0.04	−0.03	−0.01	0.6	0.6
Sex of household head					
Female	0.04*	−0.40*	−0.11†	8.4*	8.4
Male (ref.)					
Total					114

ref. = reference category.
* $P<0.01$.
† $P<0.05$. ref. = reference category.

wealth index, then inequalities in vaccination dropout would decrease by 33.6%. Furthermore, number of children under 5 years old, sex of the household head, and one-way walking distance to the nearest health facility also contributed 9.4%, 8.4%, and 8.4% to the inequality of vaccination dropout, respectively.

DISCUSSION

To the best of our knowledge, this is the first study to quantify the socioeconomic inequalities in vaccination dropout and its drivers in Ethiopia. The study decomposed the CnI into the contributions of individual factors to wealth-related inequalities impacting childhood vaccination dropout among children aged 12 to 35 months in remote and underserved settings in Ethiopia by use of a decomposition approach. The overall CnI was –0.179, and it was statistically significant ($P < 0.01$), which confirmed the concentration of vaccination dropout among the lowest wealth strata.

Our study also showed that wealth index contributed about 50% of the total inequalities in vaccination dropout. This finding is consistent with studies conducted in low- and middle-income countries,[9,14,17,32,33] where lower dropout rates and improved vaccination coverage are pro-rich. In Benin, an even higher CnI was reported among children from rich homes, emphasizing higher concentration in childhood vaccination among children of the rich.[34] A study conducted in sub-Saharan Africa showed that countries with lower vaccination coverage had higher inequalities, suggesting pro-rich coverage. As a result, they concluded that increasing coverage addresses inequalities.[35] However, a study across Gambia, Kyrgyz Republic, and Namibia showed the opposite, where receipt of all basic vaccinations was disproportionately concentrated among children from poor households. Although the difference in vaccination completion rates between rural and urban areas mainly contributed to the concentration of vaccination among the poor in the Gambia and Namibia, it was chiefly household wealth that did so in the Kyrgyz Republic.[5,6] Furthermore, in Nigeria and Guinea, vaccination dropout was more concentrated among children from the "most advantaged" backgrounds than among their counterparts.[10]

The other major contributors to inequalities in vaccination dropout were whether mothers had at least once seen an SBA (33.6%) and ANC contacts (5.7%) when they were pregnant. Mothers who had seen an SBA and had four or more ANC contacts were concentrated among people of higher socioeconomic status with a lower vaccination dropout. This might be because contacts with an SBA provide information about childbirth, newborn care, and immunization.[21,36]

The CnI for mothers who had lower educational status was negative, showing that these mothers were concentrated among people of the lowest wealth strata. The contributions of education might be due to the role that it plays in improving maternal health literacy and health care utilization behavior. Mothers with higher levels of education are also more likely to adhere to the immunization schedule, with a lower dropout rate.[4,18,31,32,37–41]

Children who were residing in rural areas and who were living in areas where it takes more than 30 minutes to get to the nearest health facility were also concentrated among people of the lowest wealth strata. Place of residence also explained –16.2% of the inequality in vaccination dropout. This finding is consistent with the findings of similar studies.[3,7,14,26,31,42,43] The inequality related to place of residence could partly be explained by challenges faced in rural areas due to less developed health infrastructure and fewer skilled providers. In rural areas, traveling long distances to get to health facilities is another reason for low basic vaccination coverage and high dropout. In addition, lack of transportation access, travel costs, and waiting time pose critical challenges for mothers to take their child for vaccination.[18,44] Vaccines are transported and stored in cold chain because they can easily be damaged by high temperatures.[45] However, health facilities in rural areas face a shortage of electric power supply to keep the cold chain equipment working, which could impede provision of vaccination services as a result of stockout of vaccines.[46] Vaccine and supply stockouts also contributed to the problem.[47] Nonfunctionality of refrigerators for vaccine storage could also affect the provision of vaccination services.[48] In contrast, a study in Ghana showed that children in rural areas were more likely to complete the required vaccinations, which might be attributed to the expansion of primary health care in rural Ghana.[49]

Ethiopia can drastically reduce the inequality in child vaccination coverage by strengthening women's utilization of health care services and the accessibility of health facilities in rural kebeles. Vietnam achieved almost equal vaccination coverage among the rich and poor in 2014 by increasing disbursement of immunization staff across all areas of the country to ensure completely free vaccination for both the rich and the poor,[50] whereas South Africa in 2016, Ghana in 2014, Burundi in 2016/2017, and Uganda in 2016 achieved little or no inequality in vaccination through increased vaccination coverage.[35]

This study had a number of noteworthy strengths. Despite the presence of active conflicts in certain study areas, the research team was able to gather data in those areas. Information gathered from various sources was used to determine childhood vaccination status. Vaccination cards, medical records, and maternal recall were used to ascertain vaccination dropout. The results were validated and verified by triangulating these three sources. Acquiring high-quality data was made possible through the use of digital tools and skilled data collectors. The decomposition of the contributing factors that drive socioeconomic inequalities in childhood vaccination dropout is of paramount importance for policymakers to address the socioeconomic disparities that exist around childhood vaccination coverage and dropout in Ethiopia.

The study's limitations included its incapacity to draw conclusions about causality and its vulnerability to biases such as nonresponse bias and recall bias, which are directly linked to the study design, i.e., cross-sectional. For IDPs and refugee settings, if an immunization card was not available, the only way to determine a child's immunization status was through the mothers'/caregivers' self-reports/recalls. In this case, misclassification may result from mothers/caregivers who lack vaccination cards, forgetting their children's vaccination status.

CONCLUSION

Predictor variables that contributed the most to socioeconomic inequalities in vaccination dropout were wealth index, place of residence, SBA, and availability of a health facility in the kebele. Policymakers in Ethiopia need to address the pro-rich inequality in childhood vaccination by strengthening women's utilization of health care services and the accessibility of health facilities in rural kebeles.

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Disclosures: The research was implemented in compliance with national and international ethical principles. The research protocol was reviewed and approved by the institutional review board of the Ethiopian Public Health Institute (416/2021). Information was collected after receiving written informed consent from the caretakers.

Authors' contributions: W. A. Alemayehu and D. A. Tsegaye wrote the concept note of the evaluation study. F. Shiferie developed the study guide, conducted field supervision during data collection, conceived the research questions, performed data analyses, interpreted results, and wrote the manuscript. S. Gebremedhin and G. Andargie developed the study guide, conducted field supervision, and reviewed the manuscript. T. G. Fenta critically reviewed the manuscript and provided guidance during the writing of the manuscript. All authors read and approved the final manuscript.

Authors' addresses: Fisseha Shiferie, Gashaw Andargie, and Dawit A. Tsegaye, Project HOPE Ethiopia Country Office, Addis Ababa, Ethiopia, E-mails: fshiferie21@gmail.com, gandargie@projecthope.org, and dtsegaye@projecthope.org. Samson Gebremedhin, School of Public Health, Addis Ababa University, Addis Ababa, Ethiopia, E-mail: samsongmgs@yahoo.com. Wondwossen A. Alemayehu, Project HOPE Headquarters, Washington, DC, E-mail: wasefa@projecthope.org. Teferi Gedif Fenta, School of Pharmacy, Addis Ababa University, Addis Ababa, Ethiopia, E-mail: tgedif@gmail.com.

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Paper III

vaccines

Article

Low Measles Vaccination Coverage and Spatial Analysis of High Measles Vaccination Dropout in Ethiopia's Underprivileged Areas

Fisseha Shiferie [1,2,*], Samson Gebremedhin [3], Gashaw Andargie [1], Dawit A. Tsegaye [1], Wondwossen A. Alemayehu [4] and Teferi Gedif Fenta [2]

1 Project HOPE Ethiopia Country Office, Addis Ababa P.O. Box 45, Ethiopia; gandargie@projecthope.org (G.A.); dtsegaye@projecthope.org (D.A.T.)
2 School of Pharmacy, Addis Ababa University, Addis Ababa P.O. Box 1176, Ethiopia; tgedif@gmail.com
3 School of Public Health, Addis Ababa University, Addis Ababa P.O. Box 1176, Ethiopia; samsongmgs@yahoo.com
4 Project HOPE Headquarters, 1220 19th Street, NW, Suite 800, Washington, DC 20036, USA; wasefa@projecthope.org
* Correspondence: fshiferie21@gmail.com

Abstract: (1) Background: Measles remains a major cause of disease and death worldwide, especially in the World Health Organization African Region. This study aimed to estimate the coverage of measles vaccinations and map the spatial distribution of measles vaccination dropout in Ethiopia; (2) Methods: A cross-sectional survey was conducted in Ethiopia's underprivileged areas. The study included 3646 mothers/caregivers of children. ArcGIS for the spatial analysis, Global Moran's I statistic for spatial autocorrelation, and Getis-Ord Gi* statistics for hot spot analysis were applied; (3) Results: Overall, coverages of measles-containing-vaccine first- and second-doses were 67% and 35%, respectively. Developing regions had the lowest coverages of measles-containing-vaccine first- and second-doses, 46.4% and 21.2%, respectively. On average, the measles vaccination dropout estimate was 48.3%. Refugees had the highest measles vaccination dropout estimate (56.4%). The hot spot analysis detected the highest burden of measles vaccination dropout mainly in the northeastern parts of Ethiopia, such as the Afar Region's zones 1 and 5, the Amhara Region's North Gondar Zone, and peripheral areas in the Benishangul Gumuz Region's Assosa Zone; (4) Conclusions: The overall measles vaccination coverages were relatively low, and measles vaccination dropout estimates were high. Measles vaccination dropout hot spot areas were detected in the northeastern parts of Ethiopia.

Keywords: measles; vaccination; spatial distribution; dropout; hot spot analysis

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1. Introduction

Measles remains a major cause of disease and death worldwide, especially in the World Health Organization (WHO) African Region (AFR) [1]. During 2017–2021, regional coverage of the measles-containing-vaccine first-dose (MCV1) remained stable at 68–70% but below the level necessary to achieve high population immunity against measles (≥95%). The low coverage of MCV1 in populous countries like the Democratic Republic of the Congo, Ethiopia, and Nigeria has largely contributed to AFR's low coverage [2,3]. Despite the existence of an effective vaccine, regions have varying success in measles control [4].

Currently, infants are receiving 11 different antigens from the Expanded Program for Immunization of Ethiopia through a combination of outreach, static, and mobile activities; services are primarily offered in health centers and health posts. Large-scale, periodic campaigns are also being used to administer the vaccines against meningitis, polio, and measles [5]. Ethiopia introduced the measles-containing-vaccine second-dose (MCV2) program in 2018 and launched it into the routine immunization program in 2019 to boost immunity and halt repeated measles outbreaks. MCV1 is given at nine months after birth for all children, and MCV2 is given at fifteen months [6,7].

Based on the Ethiopian Mini Demographic and Health Survey (EMDHS) 2019 report, the coverage of MCV1 was 59%, and the lowest coverage was in the Afar Region (28.5%) [8]. There was a persistently high incidence of measles in the Oromia Region of Ethiopia between 2011 and 2018, where 25,000 measles cases were reported [9]. A study that used the EMDHS 2019 data showed that the MCV2 coverage was 12.36% [10]. A 2022 study conducted in urban areas of the North Showa Zone of central Ethiopia estimated an MCV2 coverage of 42.5%. The primary reason for not receiving the MCV2, according to the study, was a lack of awareness of the need to return for a second dose of the measles vaccination [11]. On the other hand, a joint report of WHO and UNICEF indicated that the coverage of MCV2 in Ethiopia was 46% and 48% in 2021 and 2022, respectively [12].

Per the WHO's recommendation, the main indicators of immunization to estimate dropout include discrepancies between the first and third doses of the Diphtheria–Tetanus–Pertussis (DTP1 to DTP3), Bacillus Calmette–Guérin (BCG) vaccine to MCV1, and MCV1 to MCV2 [13]. The continuation of the childhood immunization program is evaluated using vaccination dropout rates. A dropout rate of more than 10%, according to the WHO, is undesirable and suggests that a health facility has utilization constraints. Conversely, a low dropout rate suggests high service quality due to good utilization [14–16]. Vaccination dropout using DTP1 to DTP3 and BCG to MCV1 using the same dataset had already been published. The research revealed that caregivers who worked outside the home, belonged to the lowest socioeconomic classes, did not receive follow-up care from a skilled birth attendant, did not receive postnatal care, were older than 45 years old, and lacked gender empowerment were more likely to experience vaccination dropout [17].

To eliminate measles by 2020, AFR countries and partners planned to achieve $\geq$95% with two doses of MCV coverage and improve the quality of supplemental immunization activities [8,18]. However, these goals were not met and, in 2021, coverages of MCV1 and MCV2 remained <95%. To reach the updated 2030 regional measles elimination target in at least 80% of African countries, it is imperative to administer both doses of the measles vaccine to every child and enhance surveillance [8]. Estimating the coverage of measles vaccination and understanding the geographical distribution of measles vaccination dropout is crucial to setting up appropriate interventions. This study was carried out to estimate the coverage and dropout rate of measles vaccination and map the spatial distribution of high- and low-risk areas for vaccination dropout in remote and underserved settings of Ethiopia.

2. Materials and Methods

2.1. Study Design and Settings

The data for this study were taken from a large cross-sectional evaluation survey that was conducted from May to July 2022. Areas with zero-dose and under-immunized children were first identified through a qualitative situational analysis using secondary data sources prior to the quantitative survey.

With the understanding that zero-dose and under-immunized children in low-income countries are located in underserved areas [19], the study targeted eight partly overlapping settings. In Ethiopia, developing regions are those that are governed by relatively young administrations and need more assistance to raise their level of development to that of the country's other developed regions. In addition to having less developed infrastructure, these regions' development in many other areas is progressing slowly, and border-related conflicts impede development even more. Newly established regions are those that were formed between June 2020 and November 2021. These include Sidama and Southwest Ethiopia and they were split off from Southern Nations, Nationalities, and Peoples (SNNP) (see Table 1 and Figure 1) [17,20].

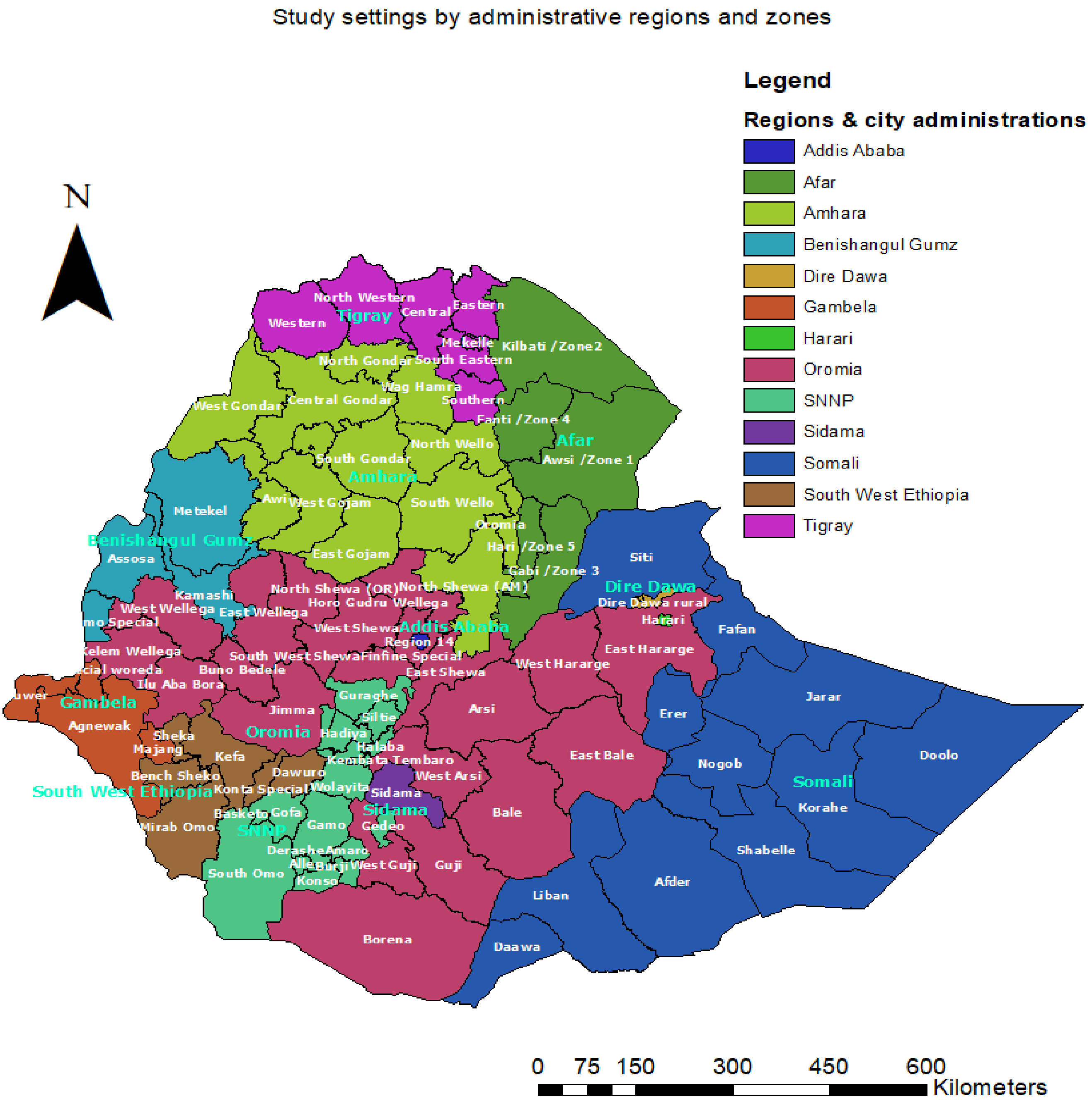

Figure 1. Study settings by administrative regions and zones.

Table 1. Target population domains and their descriptions.

	Population Domain	Description
1	Pastoralist regions and populations	Afar and Somali regions and specific pastoralist or semi-pastoralist settings in Oromia, SNNP, Southwest Ethiopia, and Gambella regions
2	Developing regions	Afar, Somali, Gambella, and Benishangul Gumuz regions
3	Newly established regions	Sidama and Southwest Ethiopia regions
4	Conflict-affected areas	Selected settings in Afar, Amhara, Oromia, and Benishangul Gumuz regions
5	Underserved urban slums	Urban slums in six selected cities (Addis Ababa, Bahirdar, Hawassa, Dire Dawa, Harar, and Adama) and rural areas under Dire Dawa City Administration and Harari Region

Table 1. *Cont.*

	Population Domain	Description
6	Hard-to-reach areas in major regions	Selected remote districts in Amhara, Oromia, and SNNP regions
7	Internally displaced populations (IDPs)	Selected IDP centers in Afar, Amhara, Oromia, and Benishangul Gumuz regions
8	Refugees	Refugees from selected camps in Somali, Afar, and Gambella regions

2.2. Study Participants

The target population for this study was children under five who lived in the identified eight partly overlapping settings. Children in the age range of 1 and 3 years were included in the study.

2.3. Sample Size Determination

The WHO 2018 immunization coverage cluster survey manual was used as a reference for the sampling design of the study [21]. The appropriate sample size for each target population was calculated using Cochran's Single Proportion Sample Size Formula [22] considering a 95% confidence level, 4% margin of error, 16% prevalence of zero-dose children [6], and 10% compensation for possible non-response. The number of children needed for a prevalence study was determined using the sample size formula below: $n = \frac{Z2p(1-p)}{d2}$, where n is the total sample size required, Z is the statistic corresponding to a 95% confidence level, which is 1.96, p represents the prevalence of children receiving zero doses in earlier studies conducted in Ethiopia, and d is precision (corresponding to effect size) [23]. Therefore, a sample size of 360 was required for every target population domain.

Based on data from the Ethiopian DHS 2016 and EMDHS 2019, there were, on average, 12 children aged 12–35 months in each enumeration area [6]. Under the assumption that every child in the EA would be qualified for study participation, a minimum of 30 EAs were needed for every population domain in order to recruit 360 children in each target population. Forty EAs were chosen at random from urban slums, and 480 children were selected [17,20].

With 360 samples per population domain, the study originally planned to include 4080 children from 340 EAs, but because of security concerns in some study districts, only 3646 children between the ages of 12 and 35 months were included in the actual survey. The overall sample size was sufficient to allow for the analysis of subgroups according to age, sex, and other pertinent background variables [17,20].

2.4. Sampling Procedure

To choose children between the ages of 12 and 35 months, a two-step procedure was employed in a cluster sampling approach. First, a random selection of EAs was made from all of the EAs that were available in each target population domain. The sampling frame was the EAs as defined by the Ethiopian Central Statistical Agency [6]. EA maps were created by skilled cartographers after hot spot urban slums in Addis Ababa, Adama, Bahir Dar, Hawassa, Harar, and Dire Dawa cities were identified and demarcated. Villages or clusters were considered as EAs for the IDP and refugee camps. After all of the eligible children in each EA were listed, 12 children were selected using a smartphone-based random number generator for inclusion in the study [17,20].

2.5. Data Collection Procedures and Data Quality Assurance

Data were gathered using pretested tools prepared in the languages of Afar, Somali, Amharic, Afan Oromo, and Sidama. The CommCare digital app version 2.52.1, an application system that is open-source, user-friendly, and compatible with popular data analytics and visualization software, was used by 48 seasoned enumerators and 24 supervisors to collect survey data. The app assisted in collecting data on individual children and households in order to ensure high-quality data collection, cleaning, and real-time monitoring [17,20].

Enumerators and supervisors who participated in the survey had at least a diploma, a great deal of experience with comparable national surveys, and knowledge of the CommCare digital app. Before being deployed, they attended a five-day training program that was led by a structured training manual. Mock interviews, field exercises, an introduction to using the CommCare digital app, an explanation of basic ethical research practices involving human subjects, the sampling approach, fundamental data collection principles, and a line-by-line discussion of the questionnaire were all covered in the training. The questionnaire was divided into ten sections excluding the information sheet and consent form section. These include basic information about the interview, sociodemographic information, household characteristics, access to health services, maternal health service utilization, knowledge and attitudes on vaccination, child immunization history, barriers and enablers to vaccination, service integration, and gender empowerment sections [17,20].

Enumerators could collect data from up to six mothers/caregivers per person per day. Supervisors conducted follow-up interviews with one-third of the study participants to confirm the quality of the data. In addition, the research team closely monitored the uploaded data throughout the survey implementation period [17,20].

2.6. Ascertainment of Childhood Vaccination

In accordance with the WHO recommendations, mothers'/caregivers' reports, immunization cards, and facility records were utilized to ascertain children's vaccination status. When presented by the mother or caregiver, the vaccination card was used to determine the child's vaccination status. If this card was not presented, the mother or caregiver's self-report was used to determine the child's immunization status. Prior research has confirmed this method's dependability for determining childhood immunization in resource-constrained environments with insufficient childhood immunization documentation [24].

2.7. Data Management and Statistical Analysis

Every day, data were gathered via the CommCare digital app [25] and kept on a local server. The CommCare digital app has built-in features to support the global positions system's data collection at the field level. The descriptive and summary statistics, such as cross-tabulations and frequency tables, were generated using STATA version 17.0 (Stata Corp. Statistical Software) [26]. ArcGIS version 10.8 was used for the spatial analysis. The data were weighted to make the survey representative. In order to balance weighted and unweighted sample sizes, linearization of post-stratification weights was made.

2.8. Measles Vaccination Coverage

Coverage was calculated as the proportion of children aged 12–35 months who received either MCV1 or MCV2. Overall MCV1 and MCV2 vaccination coverage estimates, as well as coverage estimates separately for each population domain, were computed.

2.9. Measles Vaccination Dropout

The percentage of children who received the first vaccination but did not receive the second vaccine is known as the vaccination dropout estimate. For this study, the measles vaccination dropout estimate was defined as the percentage of children who did not receive MCV2 among those who received MCV1. For the spatial analysis, measles vaccination dropout cases by the zonal administrative unit were mapped.

2.10. Spatial Autocorrelation

The distribution pattern of measles vaccination dropout cases across the study area was examined using spatial autocorrelation to determine whether dropout was dispersed, clustered, or randomly distributed. The Global Moran's I spatial statistics was used to measure spatial autocorrelation, whereby a value approaching +1 would indicate spatially clustered measles vaccination dropout cases and a value approaching −1 would suggest a dispersed spatial distribution of measles vaccination dropout cases. A Moran's I value of 0 would indicate a random geographic distribution of measles vaccination dropout cases. A statistically significant Moran's I (p-value < 0.05) would strongly suggest the presence of spatial autocorrelation and would likely lead to the rejection of the null hypothesis (measles vaccination dropout is randomly distributed).

2.11. Hot Spot Analysis (Getis-Ord Gi* Statistics)

A hot spot analysis using Getis-Ord Gi* statistics was applied to show the spatial variability of measles vaccination dropout cases. A z-score with a 95% confidence interval and a p-value < 0.05 confirmed the statistical significance of clustering. Statistical output with a high Gi* would signify measles vaccination dropout hot spots (i.e., more significant numbers of dropout children), while a low Gi* would suggest measles dropout cold spots (i.e., lower numbers of dropout children).

2.12. Ethical Approval

The research was implemented in compliance with national and international ethical principles. The research protocol was reviewed and approved by the institutional review board of the Ethiopian Public Health Institute (416/2021). Data were collected after obtaining written informed consent from the mothers/caregivers. All zero-dose children were referred to the nearest health facility using a referral form to maximize beneficence.

3. Results

3.1. Sociodemographic Characteristics

The data for this study were taken from a large cross-sectional evaluation survey, and the key findings of the original survey have already been published. With a response rate of 97.7%, 3646 mothers/caregivers of children between the ages of 12–35 months participated in the study. Among the respondents, the majority (59.2%) had no formal education, and over half (54%) were between the ages of 25–34 years. More than 81% came from rural areas, with 17% coming from the Afar region. When the survey was conducted, 57% of the respondents were unemployed, and nearly 91% of the respondents were married or living together (Table 2) [17,20].

Table 2. Sociodemographic characteristics of mothers/caregivers and their children in underserved settings of Ethiopia, 2022.

Characteristics	Frequency	Percent
Child's sex		
Male	1985	54.4
Female	1661	45.6
Child's age (months)		
12–23	1849	50.7
24–35	1797	49.3
Mother's/Caregiver's age (years)		
15–24	875	24.0
25–34	1969	54.0
35–44	572	15.7
45 or above	104	2.9
Do not know	126	3.5
Mother's/Caregiver's educational status		
No formal education or preschool	2158	59.2
Primary education	788	21.6
Secondary education	616	16.9
Tertiary education	84	2.3

Table 2. *Cont.*

Characteristics	Frequency	Percent
Marital status		
Not ever married	43	1.2
Married/Living together	3312	90.8
Separated	83	2.3
Divorced	110	3.0
Widowed	98	2.7
Place of residence		
Urban	677	18.6
Rural	2969	81.4
Caregiver's employment status		
Unemployed	2098	57.6
Employed	1548	42.4
Region *		
Afar	636	17.4
Amhara	372	10.2
Oromia	431	11.8
Somali	480	13.2
Benishangul Gumuz	216	5.9
Southern Nations, Nationalities, and Peoples	300	8.2
Sidama	239	6.6
Southwest Ethiopia	181	5.0
Gambella	479	13.1
Harari	60	1.6
Addis Ababa	192	5.3
Dire Dawa	60	1.6
Household size		
2–5	2044	56.0
6 or above	1602	44.0

* Unweighted sample size.

3.2. Coverage of Measles in Remote and Underserved Settings of Ethiopia

Coverages of MCV1 and MCV2 varied across the different target populations. The overall coverage of MCV1 was 67% and that of MCV2 was 35%. Urban slums had the highest MCV1 and MCV2 coverages, 86.8% and 54.1%, respectively. On the other hand, the lowest MCV1 and MCV2 coverages were in developing regions, 46.4% and 21.2%, respectively. Figure 2 below shows the numbers and proportions of children who had received the measles vaccines according to vaccination cards, medical records, or mothers'/caregivers' self-reports.

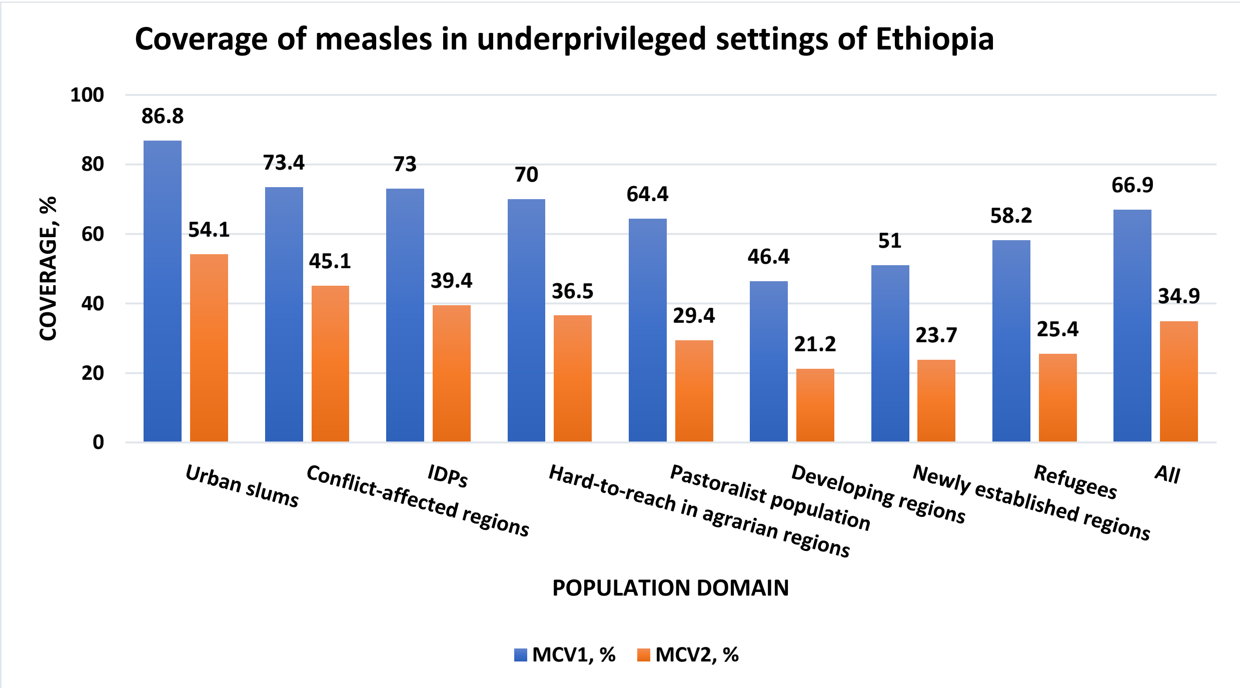

Figure 2. MCV1 and MCV2 vaccination coverages in underserved settings of Ethiopia.

3.3. Measles Vaccination Dropout Estimates in Remote and Underserved Settings of Ethiopia

The different target populations had varying measles vaccination dropout estimates. Overall, the measles vaccine dropout estimate was 48.3%. While the highest measles dropout estimate was in refugees (56.4%), urban slums had the lowest measles dropout estimate (37.7%) (Table 3).

Table 3. Measles vaccination dropout estimates across the target populations in Ethiopia, 2022.

Target Population Domain	MCV1 to MCV2 Dropout Estimate * *n* (%)
Urban slums	145 (37.7)
Conflict-affected regions	78 (38.5)
IDPs	89 (46.2)
Hard-to-reach in agrarian regions	264 (47.9)
Pastoralist population	469 (54.3)
Developing regions	348 (54.4)
Newly established regions	114 (53.5)
Refugees	102 (56.4)
All †	1158 (48.3)

† Target population groups add up to more than the total because certain populations contributed to multiple domains. * Table is only looking at participants identified as dropouts for measles from the larger study population—it does NOT account for all 3646 participants.

3.4. Spatial Autocorrelation Analysis

The spatial autocorrelation analysis revealed that the spatial distribution of measles vaccination dropout cases in Ethiopia was non-random (Global Moran's I = 0.992195, $p < 0.001$). The result showed that the observed Global Moran's I value was greater than the expected index (−0.000046) and was statistically significant. This clustered pattern has a less than 1% probability of being the result of random chance, according to the z-score of 205.881092 (Figure 3).

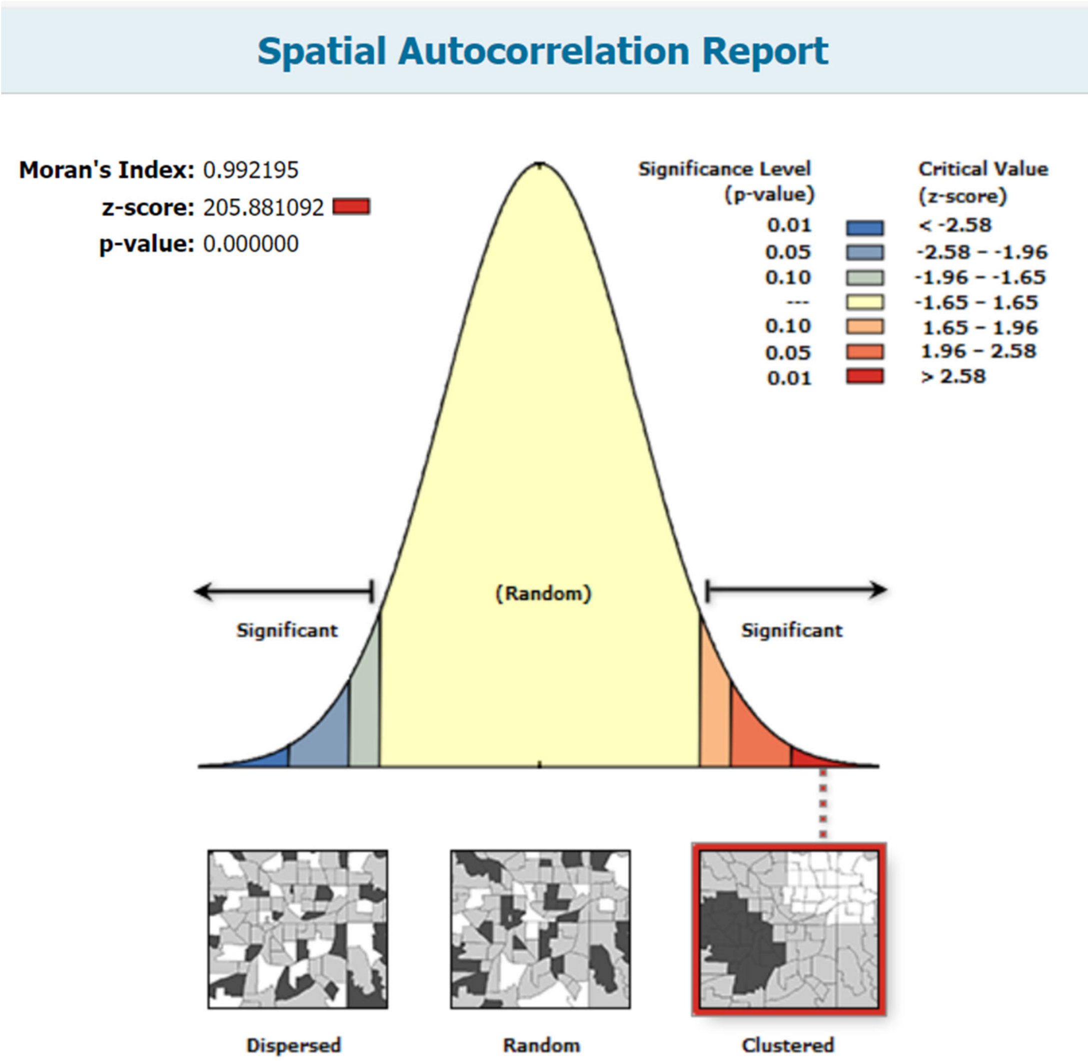

Figure 3. Spatial autocorrelation analysis of measles vaccination dropout cases in Ethiopia.

3.5. Hot Spot Analysis of Measles Vaccination Dropout Cases

The geographical distributions of measles vaccination dropout cases by zonal administrations were identified using the Getis-Ord GI* hot spot statistical analysis technique. The dark red color indicates significant ($p < 0.001$) clusters of high measles vaccination dropout (risk areas), the orange color shows zones with significant ($p < 0.001$) clusters of medium-level measles dropout cases, and the gray color indicates significant ($p < 0.001$) clusters of low measles vaccination dropout (non-risky areas). As shown in Figure 4 below, the highest burden of measles vaccination dropout cases (hot spot areas) were detected in zones 1 and 5 of the Afar Region, the North Gondar Zone of the Amhara Region, peripheral areas in the Assosa Zone of the Benishangul Gumuz Region, the Agnewak Zone of the Gambella Region, certain areas of the Harari Region, the Siti Zone of the Somali Region, the West Hararge Zone of the Oromia Region, the South Omo Zone of the SNNP Region, and in certain areas of the Addis Ababa City Administration. A relatively higher burden of measles vaccination dropout cases was also found in the West Gojjam and Waghmra zones of the Amhara Region, the Nuwer Zone of the Gambella Region, the East Wellega, East Shewa, Borena, and East Hararge zones of the Oromia Region, peripheral areas of the Addis Ababa City Administration, the Fafan and Liban zones of the Somali Region, and rural areas of Dire Dawa City. On the other hand, most parts of the Oromia, Somali, SNNP, and Amhara regions and the Southwest Ethiopia and Sidama regions were identified as cold spot areas for measles vaccination dropout cases (non-risky areas) (Figure 4).

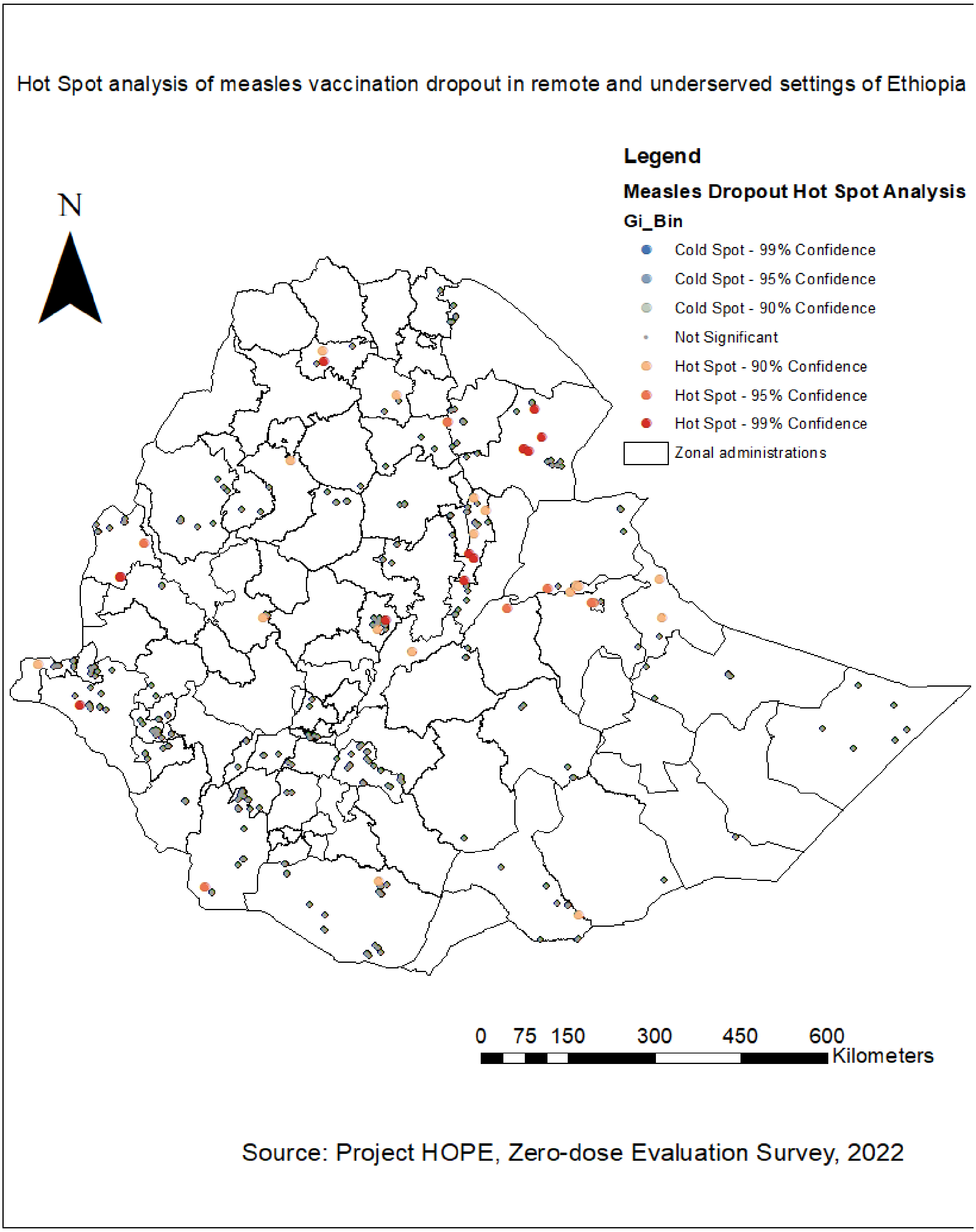

Figure 4. Hot spot analysis of measles vaccination dropout cases in Ethiopia [20].

4. Discussion

A total of 3646 mothers/caregivers with children aged 12–35 months from 340 clusters were included in the study. The coverage of childhood MCV1 and MCV2 were 67% and 35%, respectively, which were higher than the estimates from the EMDHS 2019 data of 59% for MCV1 [8,27] and 12% for MCV2 [10]. However, the MCV2 coverage result from our study was much lower than the finding presented in the 2022 joint report of the WHO and

UNICEF (48%) [12]. Our study's inclusion of underprivileged areas could possibly explain this discrepancy between MCV2 coverage estimates.

The coverage estimates for the measles vaccine varied between the different population domains. Among these target populations, urban settings had the highest MCV1 and MCV2 coverage estimates. Compared to previous studies in urban areas, the MCV2 coverage result showed a modest improvement. For instance, in underserved urban areas, the estimated coverage of MCV2 in the present study was 54.1%, which was higher than the coverage in urban areas of the North Shoa Zone in central Ethiopia (42.5%) [11]. All the childhood MCV1 and MCV2 coverages of the present study were still far below the recommended herd immunity threshold (95%) necessary to achieve high population immunity against measles. This indicates that Ethiopia and the AFR are still at high risk for measles outbreaks [28].

Overall, the measles vaccination dropout estimate was 48.3%. This was higher than the vaccination dropout estimates from the same study looking at DTP1 to DTP3 (44%) and BCG to MCV1 (21.5%) [17]. Similar to the vaccination coverage results, the measles vaccination dropout estimates varied across the different target populations. Higher measles vaccination dropout estimates were found in refugees (56.4%), pastoralist populations (54.3%), developing regions (54.4%), and newly established regions (53.5%), whereas the lowest estimate was in urban slums (37.7%). These findings are in line with a previous study that reported higher dropout estimates in pastoralist regions [29]. The present study's findings are also consistent with a study by Shiferie et al. which utilized the same dataset and found the highest vaccination dropout estimate was in newly established regions (73%) based on BCG and MCV2, whereas the lowest vaccination dropout estimates were in urban slums [17]. The delayed introduction of MCV2 into Ethiopia's routine immunization program in 2020 might have contributed to the increased MCV1 to MCV2 dropout estimate. Moreover, a lack of awareness of the need to return for MCV2 may have also led to a higher dropout estimate [11]. All the measles vaccination dropout estimates of the present study were higher compared to the WHO's 10% maximum acceptable dropout threshold. This could be a sign of the immunization programs' inadequate performance in Ethiopia's underprivileged areas [14,16].

Donors and policymakers are increasingly interested in mapping the spatial heterogeneity of childhood vaccination to identify existing gaps and intervene accordingly. The global spatial autocorrelation analysis of our data showed a clustering pattern of childhood measles vaccination dropout cases across the study areas (Global Moran's I = 0.992195, $p < 0.001$). This indicated that measles vaccination dropout cases were aggregated in specific areas. The hot spot analysis showed that the highest burden of measles vaccination dropout cases (hot spot areas) were detected in zones 1 and 5 of the Afar Region, the North Gondar Zone of the Amhara Region, peripheral areas in the Assosa Zone of the Benishangul Gumuz Region, the Agnewak Zone of the Gambella Region, certain areas of the Harari Region, the Siti Zone of the Somali Region, the West Hararge Zone of the Oromia Region, the South Omo Zone of the SNNP Region, and certain areas of the Addis Ababa City Administration.

The findings of the hot spot analysis are consistent with previous surveys and studies conducted in Ethiopia. A study on the spatial distribution of immunization defaulting in Ethiopia showed that most defaulters were in the eastern and northeastern parts of the country [30]. The previous literature also indicated that areas with low immunization were spatially clustered in the northeastern parts of the country [31–34]. Moreover, two separate studies by Tesfa et al. also showed the presence of low vaccination clusters in zones 1, 4, and 5 of the Afar Region and the Liben Zone of the Somali Region [27,35]. The high burden of measles vaccination dropout cases in northeastern parts of Ethiopia was attributed to the nomadic and pastoralist populations that move from place to place seasonally, negatively inhibiting access to health care services, including immunization [36–39]. Low utilization of health information in these parts of Ethiopia might also contribute to the high burden of measles vaccination dropout cases [40]. On the other hand, most parts of Addis Ababa, Oromia, Somali, SNNP, and Amhara regions and Southwest Ethiopia and Sidama regions were identified as cold spot areas for measles vaccination dropout cases (non-risky areas).

This study was strong in a number of ways. The research team collected data in areas where there were ongoing conflicts. Furthermore, data collected from a variety of sources, such as vaccination cards, medical records, and mother/caregiver recall, were used to determine childhood vaccination dropout. The results were validated, and the data quality was strengthened by this triangulation. The collection of high-quality data was also facilitated by the utilization of digital tools and the employment of skilled data collectors. Hot spot areas for measles vaccination dropout cases were identified using advanced geospatial analysis techniques.

However, the study also had limitations, including vulnerability to biases that are closely related to the cross-sectional study design, such as recall bias and nonresponse bias. Mothers or caregivers who lacked vaccination cards may have forgotten their child's immunization status, which could have led to misclassification.

5. Conclusions and Recommendations

The overall MCV1 and MCV2 coverage estimates were low, measles vaccination dropout was high, and there were geographical variations in both parameters across Ethiopia. The hot spot analysis showed that the highest burdens of measles vaccination dropout cases (hot spot areas) were detected mainly in the northeastern parts of Ethiopia.

Due to its recent introduction, the lack of awareness around MCV2 needs to be addressed in Ethiopia, especially in the northeastern part of the country where there were the highest estimates of measles vaccination dropout.

This study aimed to contribute to improving Ethiopia's measles vaccination coverage by providing evidence for targeted interventions. Moreover, this research could help fulfill the 2030 immunization agenda, which aims to provide everyone in the world with equitable and effective vaccines to tackle vaccine-preventable diseases in order to improve health and wellbeing.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of the Ethiopian Public Health Institute (416/2021).

Informed Consent Statement: Informed consent was obtained from the mothers/caregivers. To maximize beneficence, all children who did not receive any vaccine were referred to the nearest health facility using a referral form.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

AFR: African Region; BCG: Bacillus Calmette–Guérin; DTP1: Diphtheria–Tetanus–Pertussis-Containing-Vaccine First-Dose; DTP3: Diphtheria–Tetanus–Pertussis-Containing-Vaccine Third-Dose; EA: Enumeration rea; EDHS: Ethiopia Demographic and Health Survey; IDP: Internally Displaced Population; MCV1: Measles-Containing-Vaccine First-Dose; MCV2: Measles-Containing-Vaccine Second-Dose; SNNP: Southern Nations, Nationalities, and Peoples; WHO: World Health Organization.

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EDITED BY
Ramos Amador Jose T,
Complutense University of Madrid, Spain

REVIEWED BY
Ikechukwu Udo Ogbuanu,
Emory University, United States
Mathias Lalika,
Mayo Clinic, United States

*CORRESPONDENCE
Fisseha Shiferie
fshiferie@projecthope.org

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Spatial distribution of zero-dose children in Ethiopia: evidence for a targeted intervention from a large-scale cross-sectional evaluation survey

Fisseha Shiferie[1,2]*, Samson Gebremedhin[3], Gashaw Andargie[1], Frank DelPizzo[4], Kidist Belete[5] and Teferi Gedif Fenta[2]

[1]Project HOPE Ethiopia Country Office, Addis Ababa, Ethiopia, [2]School of Pharmacy, Addis Ababa University, Addis Ababa, Ethiopia, [3]School of Public Health, Addis Ababa University, Addis Ababa, Ethiopia, [4]Bill & Melinda Gates Foundation, Seattle, WA, United States, [5]USAID Ethiopia, Addis Ababa, Ethiopia

Background: Ethiopia is the fourth leading contributor to the global total of zero-dose children (those who lack the first dose of diphtheria-tetanus-pertussis containing vaccine) and has substantial regional variations in zero-dose children. This study explored the spatial pattern of zero-dose children aged 12–35 months in Ethiopia.

Methods: A survey was conducted in pastoralist regions, developing regions, newly-established regions, conflict-affected areas, underserved urban populations, hard-to-reach areas, internally displaced populations, and refugees. Spatial autocorrelation was measured using the Global Moran's*I*statistic. Getis-Ord Gi* statistics was applied to calculate the spatial variability of the high and low prevalence rates of zero-dose children. The spatial interpolation technique was also applied to estimate unknown values that fall between known values. Inverse distance weighting interpolation method was used to predict the risk of zero-dose children. ArcGIS version 10.8 was used for the spatial analysis.

Results: A total of 3,646 children aged 12–35 months were included in the study. The spatial distribution of zero-dose children in Ethiopia was non-random (Global Moran's $I = 0.178971$, $p < 0.001$). According to the hotspot analysis, western, eastern and northern parts of Somali and western and central parts of Afar regions had the highest load of zero-dose children (hotspot areas) followed by the Northeastern part of Amhara and southeastern part of Oromia regions. On the other hand, Southern Nations, Nationalities, and Peoples, Sidama, and the Eastern part of the Southwest Ethiopia peoples regions were identified as cold spot areas. The spatial interpolation analysis corresponded with the hotspot analysis results where western and central parts of Afar and western, eastern and northern parts of Somali regions were identified as high-risk areas for zero-dose children. However, Addis Ababa, Dire Dawa, Harari, Southern Nations, Nationalities, and Peoples, Sidama, Southwest Ethiopia Peoples, and parts of Oromia were found to be low-risk areas for zero-dose children.

Abbreviations
BCG, Bacillus Calmette–Guérin; EA, Enumeration area; EDHS, Ethiopia Demographic and Health Survey; IDP, internally displaced population; SNNP, Southern Nations, Nationalities, and Peoples; WHO, world health organization.

Conclusion: The spatial analysis identified that zero-dose children had a significant spatial variation across the study areas. High clusters of zero-dose children were detected in Afar and Somali regions. Implementing routine and mop-up vaccination campaigns in the identified hotspot areas will help Ethiopia to improve coverage and reduce immunization inequalities.

KEYWORDS

spatial analysis, zero-dose children, hotspot analysis, spatial interpolation, autocorrelation

1 Introduction

Globally, the number of zero-dose children improved from 18.1 million in 2021 to 14.3 million in 2022 (1). Zero-dose children are those who lack the first dose of diphtheria-tetanus-pertussis containing vaccine (DTP1) (2). Almost all zero-dose children live in low-and middle-income countries, especially in African and Southeast Asian regions. Despite significant progresses made in increasing the number of immunized infants, Ethiopia is still the fourth leading contributor to the global total of zero-dose children with 1.1 million zero-dose children (3).

Spatial heterogeneity of vaccination coverage can delay disease elimination, even in countries with high national vaccination coverage rates (4, 5). Spatial analysis is a statistical method used to identify spatial clusters of events to recognize areas of greater vulnerability to health hazards (6). Exploring spatial heterogeneity in childhood vaccination is gaining attention to identify immunization gaps and intervene accordingly (7). Furthermore, understanding the variation in vaccination coverage is crucial for evidence-based decision-making in the prevention and control of vaccine-preventable diseases. Detecting spatial heterogeneity is useful in indicating existing programmatic gaps affecting progress that could not be identified through the routine monitoring of vaccination coverage (8).

In different sub-Saharan African countries, there is variation with regard to vaccination coverage which leads to weakened herd immunity and unequal disease risk (9). Although no study has mapped the geographical distribution of DTP-containing vaccine alone in Ethiopia, studies have demonstrated substantial regional variations in vaccination coverage of other vaccines. According to these studies, the lowest proportion of childhood immunization was in Somali, Afar, Northwest Gambella, Western and Eastern parts of Southern Nations, Nationalities, and Peoples (SNNP) and Oromia regions and the highest in Addis Ababa and Amhara region (10–14). Southwest Afar, East and Northwest Somali were at risk of Bacillus Calmette–Guérin (BCG) vaccination coverage (15). However, high BCG vaccination coverage was observed in northern, western, and central parts of Ethiopia (16). This could be because these regions are border areas and, hence, could not access and utilize healthcare services. The lower educational status of the people who live in these regions may also contribute to the low proportion of childhood vaccination (17). Local clusters of areas with low childhood measles-containing vaccine coverage were detected in the Somali, Afar, Gambella, and Oromia regions of Ethiopia (18).

Identifying geographical variations in zero-dose children is critical to effectively prioritize and design targeted prevention and intervention programs to improve Ethiopia's national vaccination coverage. To our knowledge, the spatial distribution of zero-dose children has not yet been mapped in Ethiopia. Therefore, this study aimed to explore the spatial pattern of zero-dose children aged 12–35 months in Ethiopia.

2 Methods

2.1 Study design and settings

This research was a component of a cross-sectional assessment survey that was carried out in 2022 between May and July. A single round, cross-sectional survey design was used for the study's implementation.

In line with the understanding that nearly half of zero-dose and under-immunized children in low-income countries are from hard-to-reach communities, conflict-affected settings, or disadvantaged urban areas (19) and based on our analysis of secondary data sources that was done prior to the cross-sectional survey, this study targeted populations in the following eight partly overlapping settings.

1. Pastoralist regions and populations: Afar and Somali regions and specific pastoralist or semi-pastoralist settings in Oromia, SNNP, Southwest Ethiopia Peoples, and Gambella regions
2. Developing regions: Afar, Somali, Gambella, and Benishangul Gumuz regions
3. Newly-established regions: Sidama and Southwest Ethiopia Peoples regions
4. Conflict-affected areas: Selected settings in Afar, Amhara, Oromia, and Benishangul Gumuz regions
5. Underserved urban populations: Urban slums in six selected cities (Addis Ababa, Bahirdar, Hawassa, Dire Dawa, Harar, and Adama) and rural areas under Dire Dawa City administration and Harari region
6. Hard-to-reach areas in major regions: Selected remote districts in Amhara, Oromia, and SNNP regions
7. Internally displaced populations (IDPs): Selected IDP centers in Afar, Amhara, Oromia, and Benishangul Gumuz regions
8. Refugees: Refugees from selected camps in Somali, Afar, and Gambella regions (20, 21, 22)

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2.2 Study participants

Study participants included all children between the ages of 12 and 35 months who lived in underserved, remote, and conflict-affected areas of Ethiopia (20–22).

2.3 Sample size determination

The World Health Organization's (WHO) 2018 Vaccination Coverage Cluster Surveys manual served as the model for the study's sampling design (23). Adequate sample size for each of the target population was calculated using Cochran's Single Proportion Sample Size Formula (24) assuming 95% confidence level, 4% margin of error, 16% prevalence of zero-dose children (25), and 10% compensation for possible non-response. The following sample size formula was used to calculate the number of children required in a prevalence study: $n = \frac{Z\hat{}2p(1-p)}{d\hat{}2}$ where n is the total sample size needed, Z is the statistic corresponding to 95% confidence level which is 1.96, p is the prevalence of zero-dose children in previous studies in Ethiopia, and d is precision (corresponding to effect size) (26). Therefore, a sample size of 360 was required for each of the aforementioned target population domains (20–22).

According to the Ethiopia Demographic and Health Survey (EDHS) 2016 and Mini EDHS 2019 data, an average of 12 children between the ages of 12 and 35 months are available per enumeration area (EA). An EA is a geographic area that is surveyed by one or more census representatives. To include as many eligible children as possible per EA, the 12- to 35-month age range was selected (25, 27). Therefore, assuming all children in the EAs would be eligible for inclusion in the study, at least 30 EAs were needed to recruit 360 children for each target population domain. In urban slums, 40 EAs were randomly selected and 480 children were drawn (Table 1) (20–22).

It was originally planned to include 4,080 children from 340 EAs (a minimum of 360 sample per population domain) in the survey. However, conflicts in some study districts led to the enrollment of 3,646 children aged 12–35 months from 340 EAs in the actual survey. The sample size was sufficiently large to allow subgroup analysis based on sex, age and other pertinent background characteristics such as socioeconomic status (20–22).

TABLE 1 Total sample size and EAs required for the vaccination coverage survey, Ethiopia, 2022.

Types of study population	Number of EAs	Total sample size
Afar	30	360
Somali	30	360
Benishangul Gumuz	30	360
Gambella	30	360
Pastoralist areas in Oromia, SNNP, and Southwest Ethiopia Peoples regions	30	360
Hard-to-reach areas	30	360
Conflict-affected areas	30	360
Refugees	30	360
IDPs	30	360
Newly-formed regions: Sidama and Southwest Ethiopia Peoples regions	30	360
Urban slums	40	480
Total	340	4,080

2.4 Sampling procedure

Using a cluster sampling technique, children between the ages of 12 and 35 months were selected in two steps (20, 21, 22). First, the entire pool of EAs in each target population domain was used to randomly select EAs. The EAs defined by the Central Statistical Agency of Ethiopia for the most recent census served as a sampling frame (25). Regarding urban slums, skilled cartographers identified, delineated and created EA maps for hotspot urban slums in Addis Ababa, Adama, Bahir Dar, Hawassa, Harar, and Dire Dawa. Villages or clusters were regarded as EAs in the context of IDPs and refugee camps. Second, a smartphone-based random number generator was used to select 12 children from a list of all eligible children in each EA (20–22).

2.5 Data collection procedures and data quality assurance

Pre-tested tools prepared in Amharic, Afan Oromo, Somali, Afar, and Sidama languages were used to collect the data. The CommCare digital app version 2.53.1 (Dimagi), an open-source and user-friendly application system that is interoperable with popular data analytics and visualization software (28), was used by 48 experienced enumerators and 24 supervisors to collect the survey data. The CommCare app helped to collect individual child-level and household information to ensure high-quality data collection, cleaning, and monitoring in real time. The digital app has also built-in features to support the global positions system data collection at the field level (20–22).

The recruitment of enumerators and supervisors was based on their educational background (at least diploma holders in a health-related field), familiarity with the CommCare digital app and previous experience in similar national surveys. A 5-day training guided by a structured training manual was provided to the enumerators and supervisors prior to deployment. An explanation of the sampling techniques, fundamentals of data collection, line-by-line discussion on the questionnaire, a synopsis of utilizing the CommCare digital app, mock interviews, field practice, and a review of basic ethical practices of research involving human subjects were all covered in the training (20–22).

Data collectors were allowed to collect data from up to six individuals per person per day. The supervisors re-interviewed one third of all the study participants to validate the quality of the data. Over the duration of the survey's implementation, the uploaded data were closely monitored by the research team (20–22).

2.6 Ascertainment of childhood vaccination

The vaccination status of each child was determined based on three distinct sources of information, as recommended by the

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WHO: vaccination cards, reports from the caregiver, and reports from the facility. Vaccination card was used to determine the child's immunization status in areas where the mother or caregiver had shown one. In situations when a vaccination card was unavailable, the mother's or caregiver's self-reports and recalls were used to determine the immunization status. The reliability of this approach to determine childhood vaccination in resource-constrained environments with inadequate childhood immunization records has been demonstrated by prior research (29).

2.7 Data management and spatial analysis

The data was stored in a local server on a daily basis. The descriptive and summary statistics, such as cross-tabulations and frequency tables, were generated using STATA version 17.0 (StataCorp, College Station, TX) (30). ArcGIS version 10.8 (Esri, California) was used for the spatial analysis (31). The data were weighted to make the survey representative. In order to balance weighted and unweighted sample size, linearization of post-stratification weights was made.

2.7.1 Zero-dose children

The zero-dose children are those who lack the first dose of DTP1 (2).

2.7.2 Spatial autocorrelation

In this study, spatial autocorrelation indicated whether the distribution pattern of zero-dose children aged 12–35 months across the study area was dispersed, clustered, or randomly distributed. The Global Moran's I spatial statistics was used to measure spatial autocorrelation by taking the entire data set. Moran's I is a statistic that produces a single output number between −1 and +1, and, for this study, a Moran's I value approaching +1 indicated that zero-dose children were spatially clustered. A Moran's I value approaching −1 indicated a dispersed spatial distribution of zero-dose children and a Moran's I value of 0 indicated a random geographic distribution of zero-dose children. A statistically significant Moran's I test confirmed the presence of a significant spatial autocorrelation ($p < 0.05$) and led to the rejection of the null hypothesis (zero-dose children were randomly distributed).

2.7.3 Hotspot analysis (Getis-Ord Gi* statistics)

The spatial variability of the high and low prevalence rates of zero-dose children among children aged 12–35 months was calculated using Getis-Ord Gi* statistics in a hotspot analysis. The statistical significance of clustering was confirmed using the Z-score with a 95% confidence interval and a p-value <0.05. Statistical output with a high Gi* signifies zero-dose children hotspots (i.e., larger numbers of zero-dose children), while a low Gi* indicates zero-dose children cold spots (i.e., lower numbers of zero-dose children).

2.7.4 Spatial interpolation

The spatial interpolation technique was applied to predict unknown values that fall between known values. Inverse distance weighting interpolation method was used to predict the risk of zero-dose children.

2.8 Ethical approval

The research was implemented in compliance with national and international ethical principles. The research protocol was

TABLE 2 Sociodemographic characteristics of respondents in underserved settings of Ethiopia, 2022.

Characteristics	Frequency ($n = 3,646$)	Percent
Child's sex		
Boy	1,985	54.4
Girl	1,661	45.6
Child's age (months)		
12–23	1,849	50.7
24–35	1,797	49.3
Respondent's age (years)		
15–24	875	24.0
25–34	1,969	54.0
35–44	572	15.7
45 or above	105	2.9
Do not know	126	3.5
Respondent's educational status		
No formal education or preschool	2,158	59.2
Primary education	788	21.6
Secondary education	616	16.9
Tertiary education	84	2.3
Marital status		
Not ever married	43	1.2
Married/living together	3,312	90.8
Separated	83	2.3
Divorced	110	3.0
Widowed	98	2.7
Place of residence		
Urban	677	18.6
Rural	2,969	81.4
Caregiver's employment status		
Unemployed	2,098	57.6
Employed	1,548	42.4
Region[a]		
Afar	636	17.4
Amhara	372	10.2
Oromia	431	11.8
Somali	480	13.2
Benishangul Gumuz	216	5.9
SNNP	300	8.2
Sidama	239	6.6
Southwest Ethiopia Peoples	181	5.0
Gambella	479	13.1
Harari	60	1.6
Addis Ababa	192	5.3
Dire Dawa	60	1.6
Household size		
2–5	2,044	56.0
6 or above	1,602	44.0

[a]Unweighted sample size.

reviewed and approved by the institutional review board of the Ethiopian Public Health Institute (416/2021). Information was collected after obtaining written informed consent from the caretakers. To maximize beneficence, all zero-dose children were referred to the nearest health facility using a referral form.

3 Results

3.1 Sociodemographic characteristics

The study included 3,646 mothers/caregivers who had children between the ages of 12 and 35 months. The response rate for the study was 97.7%. Of the respondents, 54% were between the ages of 25 and 34, and 59.2% had not received any formal education. Over 81% of those surveyed were from rural areas, and 17% were from the Afar region. At the time of the survey, 57% of respondents were unemployed, and over 90% of respondents were married or living with their partner (Table 2) (21).

3.2 Spatial autocorrelation analysis

The spatial autocorrelation analysis revealed that the spatial distribution of zero-dose children aged 12–35 months in Ethiopia was non-random (Global Moran's $I = 0.178971$, $p < 0.001$). The result showed that the observed Global Moran's I value was greater than the expected index (−0.000046) and the p-value was <0.01, which was statistically significant. The Z-score of 37.417977 indicated that there was a less than 1% likelihood that this clustered pattern could be the result of random chance (Figure 1).

3.3 Hotspot analysis of zero-dose children

The dark red color indicates significant ($p < 0.001$) clusters of high zero-dose children (risk areas), whereas the dark blue color indicates significant ($p < 0.001$) clusters of low zero-dose children (non-risky areas). Hence, western, eastern and northern parts of Somali and western and central parts of Afar regions were identified to have high zero-dose children (hotspot areas) followed

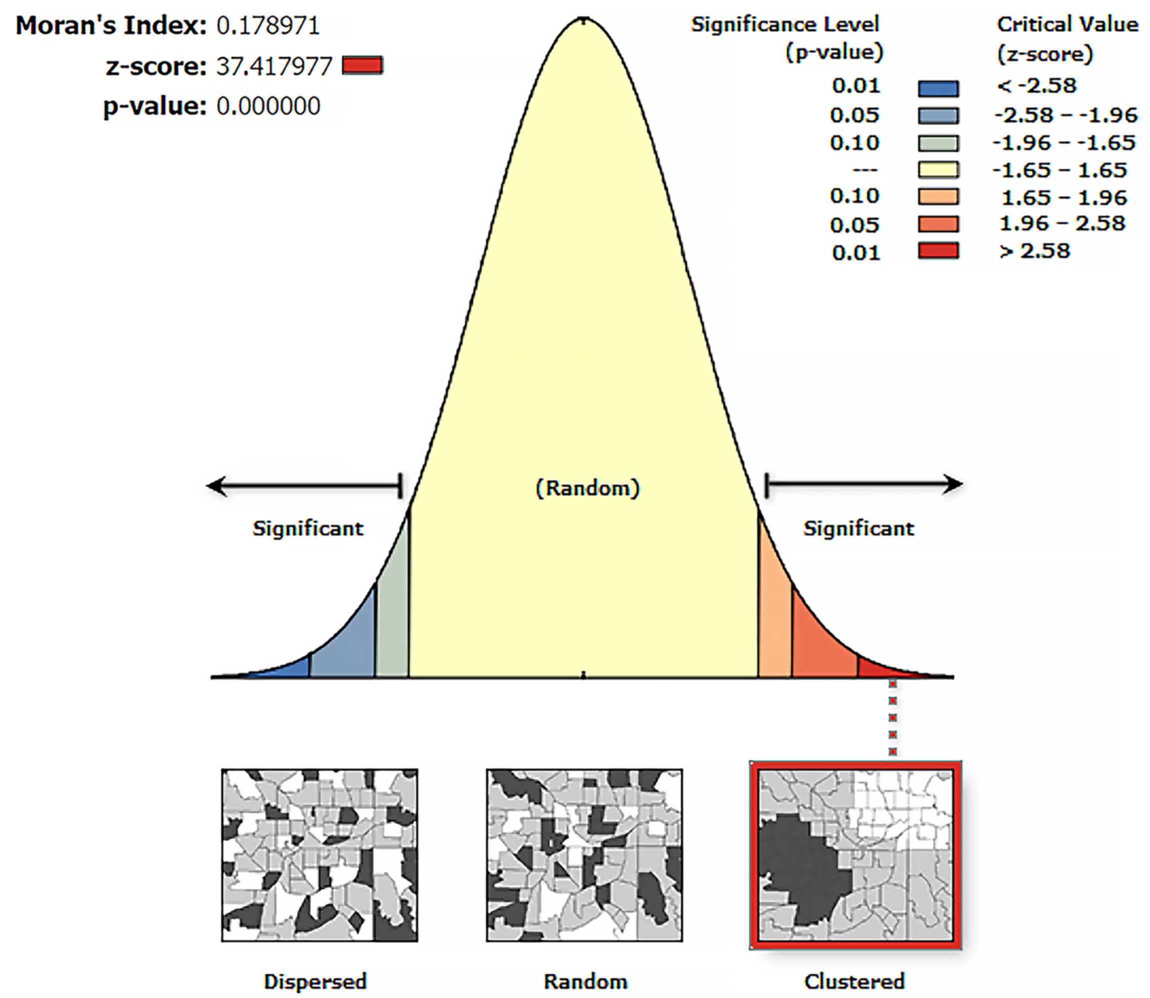

FIGURE 1
Spatial autocorrelation analysis of zero-dose children in Ethiopia, a cross-sectional evaluation survey.

by the Northeastern part of Amhara and southeastern part of Oromia regions. On the other hand, SNNP, Sidama, and the Eastern part of Southwest Ethiopia Peoples regions were identified as cold spot areas for zero-dose children (non-risky areas) (Figure 2).

3.4 Interpolation of zero-dose children

Western and central parts of Afar and western, eastern and northern parts of Somali regions were identified as riskier areas for zero-dose children followed by the Northeastern part of Amhara and southeastern part of Oromia regions. However, Addis Ababa, Dire Dawa, Harari, SNNP, Sidama, Southwest Ethiopia Peoples, and parts of Oromia were found to be low-risk areas for zero-dose children (Figure 3).

4 Discussion

To our knowledge, this is the first study to map the spatial distribution of zero-dose children in Ethiopia. The study aimed to explore the spatial pattern of zero-dose children aged 12–35 months in Ethiopia. According to this study, a spatial variation of zero-dose children was observed across the study areas. The spatial autocorrelation analysis revealed that the spatial distribution of zero-dose children in Ethiopia was non-random (Global Moran's $I = 0.178971$, $p < 0.001$). Hotspot analysis of the data showed that high zero-dose children (hotspot areas) were observed in western and central parts of Afar and western, eastern and northern parts of Somali regions. The spatial interpolation analysis corresponded with the hotspot analysis results where western and central parts of Afar and western, eastern and northern parts of Somali regions were identified as high-risk areas for zero-dose children. Conversely, cold spot areas were observed in Addis Ababa, Dire Dawa, Harari, SNNP, Sidama, and the Eastern part of Southwest Ethiopia Peoples.

Our study's findings about the spatial distribution of zero-dose children in Ethiopia are consistent with the findings of the 2016 and 2019 EDHS studies which did further analysis on the EDHS datasets and other similar studies conducted in Ethiopia. These surveys and studies showed that the spatial clustering of low

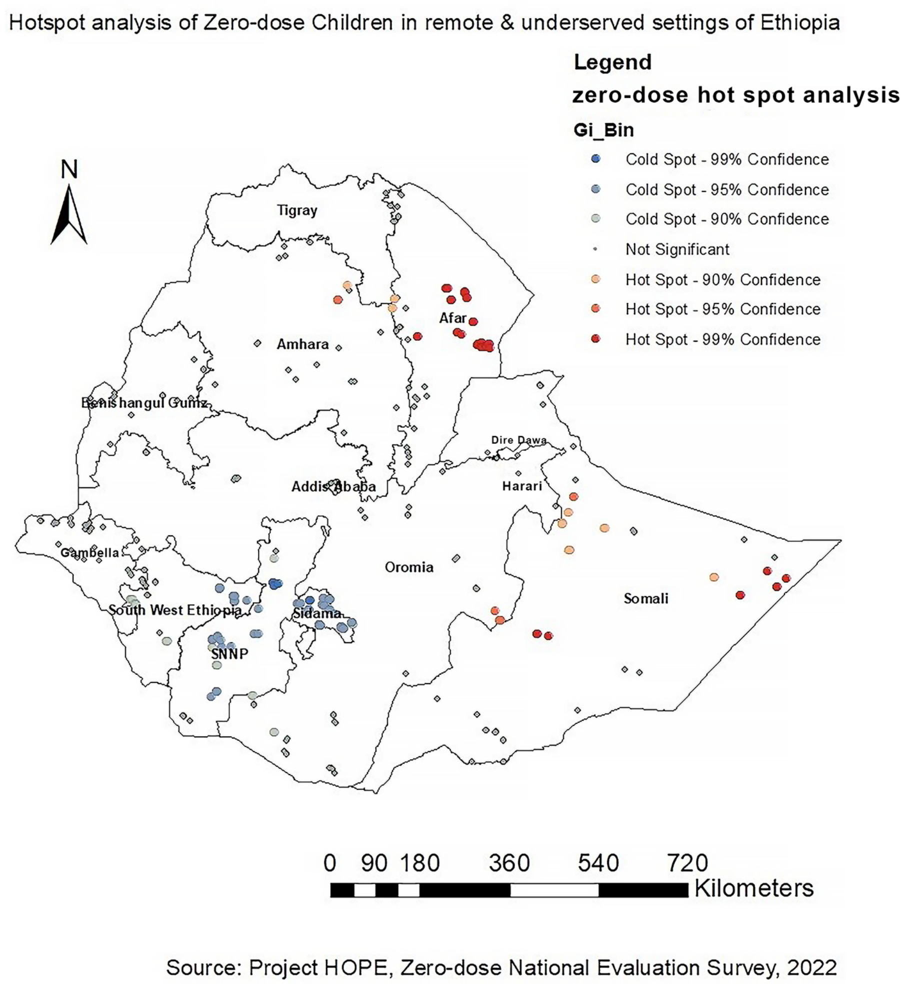

FIGURE 2
Hotspot analysis of zero-dose children in Ethiopia, a cross-sectional evaluation survey.

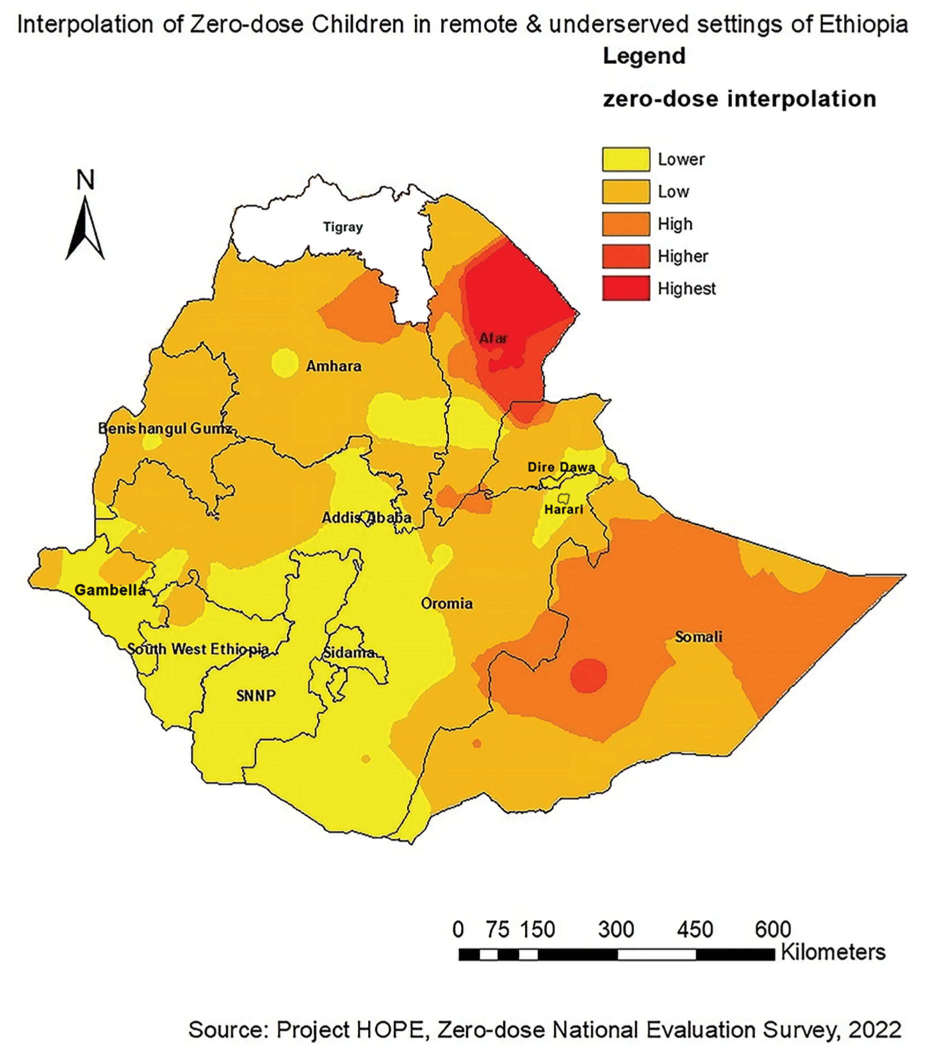

FIGURE 3
Interpolation of zero-dose children in Ethiopia, a cross-sectional evaluation survey.

immunization coverage was observed in the Eastern and Northeastern parts of the country (12, 16, 27, 32–34). Furthermore, a study done on the geographical variations of immunization defaulting in Ethiopia also showed that most of the hotspot areas (high default value) were located in the eastern (Somali) and northeastern (Afar) parts of the country, whereas most cold spot areas (low default rates) were located in Addis Ababa, Dire Dawa, and Harari (35). Our findings also aligned with the geographical distribution of low childhood measles-containing vaccine coverage where significant clusters were detected primarily in Afar and Somali regions (18, 34).

Explaining the predictors of zero-dose children is as important as mapping their spatial distribution. Predictors of zero-dose children aged 12–35 months in remote and underserved settings of Ethiopia were identified in a separate study. According to this study, living in pastoralist and developing regions was a statistically significant predictor of zero-dose children. This, in turn, was due to mothers'/caregivers' lack of or lower educational status, unavailability of public health facilities, and suboptimal healthcare-seeking behavior (22). This is in alignment with previous studies conducted in pastoralist regions of Ethiopia. According to these studies, the higher prevalence of zero-dose children in Afar and Somali regions may be due to lower health care seeking behaviors, immunization coverage, and vaccine uptake. Moreover, these regions have areas that are hard to reach with nomadic and pastoralist inhabitants who do not have permanent residences (11, 36, 37). The high burden of zero-dose children in Afar and Somali regions might also be ascribed to the existing health care systems that are in the hands of settled populations and rarely have access to nomads due to cultural, political and economic obstacles. Nomadic and pastoralists populations also move seasonally from place to place, which negatively inhibits access to health care services, including immunization (38). Low utilization of health information in these parts of Ethiopia might also contribute to the high burden of zero-dose children (39).

This study also identified the existence of spatial disparities among the different study settings. According to findings of a study that is part of the same cross-sectional survey, these observed disparities in the distribution of zero-dose children in Ethiopia could be attributed to religious beliefs, cultural norms, fear of vaccine side effects and lack of awareness and sustained interventions (40).

Reaching zero-dose children is hampered by a variety of complex obstacles unique to each setting (41). The problem can be addressed by designing-context specific interventions including strengthening horizontal integration of immunization services with other maternal & child health services such as antenatal and postnatal care, sick childcare, nutritional screening, growth monitoring, and family planning; empowering women; strengthening outreach campaigns, supplementary immunization activities (SIAs); Periodic Intensification of Routine Immunization (PIRI); strengthening outreach and static immunization services; providing incentives for health staff; bolstering immunization budget; planning to establish Men Development Army to promote engagement of men in maternal and child health services (20, 21, 40).

This study had several strengths worth mentioning. To the best of our knowledge, this is the first study to map zero-dose children in Ethiopia. Although study settings included areas where there were active conflicts, the study team still managed to collect data in those areas. Ascertainment of child vaccination dropout was based on information gathered from multiple sources. Vaccination cards, medical records, and maternal/caregiver recall were used to ascertain vaccination dropout. This triangulation helped to validate the results and strengthen the quality of the data. Similarly, the use of digital applications and experienced data collectors helped to ensure the gathering of high-quality data. Hotspot areas for zero-dose children were identified using advanced geospatial analyses techniques.

However, the study also had some limitations, including the inability to establish temporal relationships between geospatial covariates and the outcome variable. Another barrier may have been the study's susceptibility to biases, such as nonresponse bias and recall bias, which are directly linked to the cross-sectional design. Mothers and caregivers who did not possess vaccination cards may have forgotten their child's immunization status, which ultimately could have led to misclassification.

5 Conclusion and recommendations

The spatial analysis identified that zero-dose children had a significant spatial variation across the study areas. High clusters of zero-dose children were detected in western and central parts of Afar and western, eastern and northern parts of Somali regions followed by the Northeastern part of Amhara and southeastern part of Oromia region.

The findings of our study will be of great importance to guide policymakers in Ethiopia in designing and implementing routine and mop-up vaccination campaigns in the identified hotspot areas to reduce zero-dose children, thereby improving the country's immunization coverage. Moreover, this study might contribute to achieving the 2030 immunization agenda aimed at providing effective and equitable vaccines to everyone, everywhere in the world to realize better health and well-being through avoiding vaccine-preventable diseases.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Institutional Review Board of the Ethiopian Public Health Institute (416/2021). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

FS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SG: Supervision, Writing – review & editing. GA: Supervision, Writing – review & editing. FD: Funding acquisition, Resources, Writing – review & editing. KB: Funding acquisition, Resources, Writing – review & editing. TF: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDICES

APPENDIX 1

Survey Questionnaire

Project HOPE

Reaching zero dose and under immunized children in remote areas of Ethiopia

Assessment of vaccination coverage among children 12-35 months in underserved areas of Ethiopia

Introduction and Consent

Introduction/Purpose: My name is______ and I'm working for Project HOPE. We are conducting an assessment on immunization coverage among children 12-35 months in your area. We would very much appreciate your participation in this survey since you are a mother/caregiver of a child 12-35 months living in ______ kebele. In total, 3,600 mothers or caregivers will be asked to take part in this study.

Procedures: If you agree to take part in this study, I would like to ask you about the vaccination status of the child. This information will help us to plan better immunization services in your area. The questionnaire normally takes about 30 minutes to complete. Additionally, we would like to examine the vaccination records of your child. Further, my field supervisor may visit your household and ask you few questions in order to countercheck the information I collected from you.

Risks and benefits: We believe there are no risks to you or your child from participating in this study. Your child should not experience any discomfort whatsoever. Taking part in this research study may not benefit you personally, but we may learn new things that will help others.

Compensation: You will not be paid for participating in this study.

Confidentiality: We will keep your answers confidential to the best of our ability. We will not share your answers with any of your neighbors or family. We will use a number instead of your name on study forms. Your name and other facts that might help people recognize you will not appear when we present this study to others or publish its results. Any information that might identify you will be kept separate from your answers, and your answers will be kept in a secure place for analyses by the researchers only.

Voluntary participation and withdrawal: Taking part in this study is voluntary. You can choose not to talk to us or ask us to leave, and if you do agree to participate you can stop the interview at any time or skip any questions that you don't want to answer. There are no right or wrong answers. We just want to hear more about your own ideas and experiences. Also, after finishing the interview, you can refuse to have your answers included in the study. Whether or not you choose to participate will not affect the services you receive from the health system in any way.

Contact Persons: If you have any questions, I will be happy to answer them. And in case you ever want to contact someone from the office we work for, please call at the following number: +251116622123. If you wish to contact someone from the institutional review board that approached the study, please contact the Institutional Review Board Office by calling ___________.

Comprehension check: Do you have any questions about the survey? Please let me know if anything I have stated is not clear and I will be happy to explain it further to ensure you understand.

Do you accept participating in the survey? Yes_______ No__________

____________________________ ___________

Name and signature of the participant *Date*

Section I: Basic information about the interview			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
101	Date of interview (dd/mm/yy) *In Gregorian calendar*	|___|___|/|___|___|/|___|___|	
102	Team number	|___|___|	
103	Supervisors' name		
104	Interviewers' name		
105	Region	Tigray…(01) Afar…(02) Amhara…(03) Oromiya…(04) Somali…(05) Benishangul-Gumuz…(06) SNNPR…(07) Sidama…(08) Southwestern…(09) Gambella…(10) Harari…(11) Addis Ababa city administration…(12) Dire Dawa city administration…(13)	
106	Name of the woreda		
107	Name of the kebele/IDP center/refugee camp		
108	EA code	|___|___|___|___|___|___|___|___|___|___| NA…(99)	
109	Language of interview	Amharic…(01) Afan Oromo…(02) Tigrigna…(03) Afar…(04) Somali…(05) Sidaamu Afoo…(06) If other (specify)…(96)	
110	Number of visits to household by the interviewer	First…(01) Second…(02) Third…(03)	
111	Translator used?	No…(01) Yes…(02)	
112	Time the interview started *Local time, 12-hour clock (AM/PM)*	|___|___|: |___|___| |___|___|	

Section II: Socio-demographic information			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
201	Full name of the child		
202	Age of [Name] in months *Age in completed months*	|___|___| months I don't know/not sure…(98)	
203	Date of birth of [Name] *In Ethiopian calendar* *If "don't know" enter "98"*	|___|___| Day |___|___| Month |___|___| Year	
204	Sex of [Name]	Boy…(01) Girl…(02)	
205	Relationship of caregiver to [Name]	Mother…(01) Father…(02) Other primary caregiver…(03)	
206	Sex of the respondent	Male…(01) Female…(02)	
207	Age of the respondent *In completed years* *If "don't know" enter "98"*	|___|___| Years Don't know/Not sure…(99)	
208	What is the highest level of school you completed?	No formal education…(01) Preschool…(02) Primary education (1-6)…(03) Secondary education (7-12)…(04) Tertiary education…(05)	
209	Can you read in any language?	Yes…(01) No…(02)	If 208 = 01
210	Number of years of formal education	|___|___| Years	If 208 = 03 or 04 or 05
211	What is your current marital status?	Single (not ever married)…(01) Married/living together…(02) Separated…(03) Divorced…(04) Widowed…(05)	
212	What is your religion?	Orthodox…(01) Catholic…(02) Protestant…(03) Muslim…(04) Traditional…(05) If other (specify)…(96)	
213	Place of residence	Urban…(01) Rural…(02)	
214	What is your main occupation? That is, what kind of work do you mainly do?	Unemployed…(01) Housewife…(02) Unskilled manual…(03) Skilled manual…(04) Agriculture…(05) Petty trade…(06) Trade…(07) Solider/guard/police…(08)	

		Driver…(09) Professional…(10) Student…(11) Retired…(12) If other (specify)…(96)	
215	Educational status of your husband/ partner	No formal education…(01) Preschool…(02) Primary education (1-6)…(03) Secondary education (7-12)…(04) Tertiary education…(05) Don’t know/Not sure…(99)	If 211 = 01
216	What is your (husband's/partner's) occupation? That is, what kind of work does he mainly do?	Unemployed…(01) Housewife…(02) Unskilled manual…(03) Skilled manual…(04) Agriculture…(05) Petty trade…(06) Trade…(07) Solider/guard/police…(08) Driver…(09) Professional…(10) Student…(11) Retired…(12) If other (specify)…(96)	If 211 = 01
217	Sex of the household head	Male…(01) Female…(02)	
218	Relationship of the respondent to the household head	HH head…(01) Wife/Husband…(02) Son or daughter…(03) Grand child…(04) Parents (& in-laws)…(05) Brother/sister (& in-laws)…(06) Not related…(07) Other relative…(96)	
219	Do you own a mobile telephone?	Yes…(01) No…(02)	

Section III: Household characteristics			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
301	What is the roofing material (for the main house)? *Check with your observation* *Select one primary material only*	Corrugated material…(01) Thatch or grass…(02) Wood and mud…(03) Reed or bamboo…(04) Concrete/Cement/Brick tiles…(05) Plastic…(06) If other (specify)…(96)	
302	What is the floor material (for the main house)? *Check with your observation* *Select one primary material only*	Mud/dirt alone/cow dung…(01) Bamboo/wood (not finished)…(02) Wood (finished)…(03) Concrete/Cement/Tiles…(04) ______If other (specify)…(96)	
303	What is the wall material (for the main house)? *Check with your observation* *Select one primary material only*	Wood and mud…(01) Wood or reed and bamboo…(02) Plywood or other finished wood…(03) Stone and mud or stone alone…(04) Plastic or fabrics…(05) Corrugated material…(06) Concrete/Bricks and cement /Stone and cement …(07) If other (specify)…(96)	
304	What type of fuel does your household mainly use for cooking?	Electricity…(01) LPG/Natural gas/Biogas…(02) Kerosene…(03) Coal/Charcoal…(04) Wood…(05) Crop residue/straw/shrubs/grass…(06) Animal dung…(07) If other (specify)…(96)	
305	Is the cooking usually done in the house, in a separate building, or outdoors?	In the house…(01) In a separate room/kitchen…(02) Outdoors…(03) If other (specify)…(96)	
306	How many rooms in this household are used for sleeping?	|___|___| No of sleeping Rooms	
307	Are there any windows in the house? *Check with your observation*	Yes…(01) No…(02)	
308	Does this household own any livestock, herds, other farm animals, or poultry?	Yes…(01) No…(02)	> 310

309	How many of the following animals does this household own? *If "0" enter "00"*		
A	Milk cows, oxen?	|___|___|	
B	Other cattle?	|___|___|	
C	Horses, donkeys, or mules?	|___|___|	
D	Camels?	|___|___|	
E	Goats?	|___|___|	
F	Sheep?	|___|___|	
G	Chickens or other poultry?	|___|___|	
H	Beehives?	|___|___|	
310	Does any member of this household own any agricultural land?	Yes…(01) No…(02)	 > 309
311	How many hectares of agricultural land do members of this household own? *If "don't know" enter "99"*	|___|___|.|___|___| hectares Not willing to respond…(95) Don't know…(99)	
312	Does any member of this household own any land residential/housing purpose?	Yes…(01) No…(02)	 > 313
313	How many m^2 of residential/housing land do members of this household own? *If "don't know" enter "99"*	|___|___|.|___|___| m^2 Not willing to respond…(95) Don't know…(99)	
314	Does your household or member of the household have the following functional items?		

A	A watch or clock	Yes…(01)	No…(02)
B	A radio	Yes…(01)	No…(02)
C	A television	Yes…(01)	No…(02)
D	CD/DVD player	Yes…(01)	No…(02)
E	A mobile telephone	Yes…(01)	No…(02)
F	A non-mobile telephone	Yes…(01)	No…(02)
G	A refrigerator	Yes…(01)	No…(02)
H	A Table	Yes…(01)	No…(02)
I	A chair	Yes…(01)	No…(02)
J	An electric mitad	Yes…(01)	No…(02)
K	Pressure lamp	Yes…(01)	No…(02)
L	A kerosene lamp	Yes…(01)	No…(02)
M	Torch	Yes…(01)	No…(02)
N	A bicycle	Yes…(01)	No…(02)
O	A motorcycle	Yes…(01)	No…(02)
P	An animal – drawn cart	Yes…(01)	No…(02)
Q	A bajaj	Yes…(01)	No…(02)
R	Car or truck	Yes…(01)	No…(02)

315	Does your household have electricity?	Yes…(01) No…(02)	

316	Do you have any kind of health insurance for members of your household for the last one year?	Yes…(01) No…(02)	
317	If answer is 'Yes' for 313, write the type of health insurance?	Community Health Insurance…(01) Social Health insurance…(02) Private Health Insurance…(03) Don't know…(99)	
318	Does any member of this household have a bank account?	Yes…(01) No…(02)	
319	What is the main source of drinking water for members of your household? *Select one primary source only*	Piped into dwelling…(01) Piped into yard or plot…(02) Public tap/standpipe…(03) Tube well/borehole…(04) Protected well…(05) Unprotected well…(06) Protected spring…(07) Unprotected spring…(08) Rainwater collection…(09) Tanker-truck…(10) Cart with small tank/drum…(11) Surface water…(12) Bottled water…(13) If other (specify)…(96)	
320	What does this household mainly use for disposal of human urine and feces? *Select one primary source only*	Flush to sewer or septic system…(01) Simple pit latrine with floor/slab…(02) Pit latrine without floor/slab…(03) VIP with floor/slab .... (04) Composting/dry latrine........................... (05) Bucket latrine .... (06) No facility, field, bush, plastic bag......... (07) If other (specify)…(96)	
321	Total number of household members	|___|___|	
322	Total number of under five children in the household	|___|___|	

Section IV: Access to health service			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
401	In there any health facility in your kebele?	Yes…(01) No…(02)	
402	What is the nearest health facility to your household?	Health Post…(01) Health center…(02) Public hospital…(03) Private clinic…(04) If other (specify)…(96) Don't know…(99)	
403	How long does it take for you to walk to the nearest health facility? *If < 1hr record in minutes*	|___|___|: |___|___| Hours Minutes	
404	In the last 3 months, was this household visited by a health extension worker?	Yes…(01) No…(02) Not aware of HEWs…(95) Not sure/Don't know…(99)	 > 407 > 407 > 407
405	In the last 3 months, how many times did the HEWs visit this household?	|___|___| visits Don't know …(99)	
406	During the most recent visit of the HEW had in the last 3 months, what specific health messages were discussed? *Multiple responses possible* Probe, anything else?	Exclusive breastfeeding for 6 mos…(01) Complementary feeding…(02) Promotion of postnatal care…(03) Growth monitoring of children…(04) Vaccination…(05) Sanitation and waste disposal…(06) Family planning…(07) If other (specify)…(96)	
406	In the last 1 month, was this household visited by a health extension worker?	Yes…(01) No…(02) Not sure/Don't know…(99)	
407	In the last 3 months, was this household visited by a health development army (HDA) member/volunteer?	Yes…(01) No…(02) Not aware of HDA/volunteer…(95) Not sure/Don't know…(99)	 > 501 > 501 > 501
408	In the last 3 months, how many times did the health development army member/volunteer visit this household?	|___|___| visits Don't know …(99)	
409	During the most recent visit the HDA/volunteer had in the last 3 months, what specific health messages were discussed? *Multiple responses possible* Probe, anything else?	Exclusive breastfeeding for 6 mos…(01) Complementary feeding…(02) Promotion of postnatal care…(03) Growth monitoring of children…(04) Vaccination…(05) Sanitation and waste disposal…(06) Family planning…(07) If other (specify)…(96)	
410	In the last 1 month, was this household visited by a HDA/volunteer?	Yes…(01) No…(02) Not sure/Don't know…(99)	

Section V: Maternal health service utilization			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
501	When you were pregnant with [NAME], did you receive antenatal care form a health worker?	Yes…(01) No…(02) Not sure/Don’t know…(99) Not applicable…(95)	 > 505 > 505 > 505
502	When you were pregnant with [NAME], where did you go for antenatal care? *Multiple responses possible*	Health post…(01) Health center…(02) Public hospital…(03) Private hospital or clinic…(04) NGO clinic/health center…(05) Home…(06) If other (specify)…(96)	
503	When you were pregnant with [NAME], how many ANC visits have you had?	|___|___| visits Not sure/Don’t know…(99)	
504	During the ANC, did you receive any information about childhood vaccination?	Yes…(01) No…(02) Not sure/Don’t know…(99)	
505	Who assisted with the delivery of [NAME]? *Probe: anyone else?*	No one…(01) Health professionals (Doctor/nurse/midwife….)…(02) Health Extension worker…(03) Traditional birth attendant…(04) Family/relative/friend…(05) If other (specify)…(96)	
506	Where did you give birth to [NAME]?	Own home…(01) other home…(02) Health post…(03) Health center…(04) Public hospital…(05) Private hospital or clinic…(06) NGO clinic/health center…(07) Maternity home…(08) If other (specify)…(96)	
507	I would like to ask you about checks on your or [NAME]’s health after delivery, for example, someone asking you questions about your or [NAME]’s health or examining you or your baby. Within the first 6 mos of delivery, did anyone check on your or [NAME]’s health?	Yes…(01) No…(02) Not sure/Don’t know…(99)	
508	Within the first 6 months of birth, who checked on your or [NAME]’s health? *Multiple responses possible*	Health professionals (Doctor/nurse/midwife….)…(01) Health Extension worker…(02) Traditional birth attendant…(03) If other (specify)…(96)	
509	During this check, did you receive any information about childhood vaccination?	Yes…(01) No…(02) Not sure/Don’t know…(99)	

Section VI: Knowledge and attitudes on vaccination			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
601	Have you ever heard about vaccination for children?	Yes…(01) No…(02)	 > 701
602	What are the advantages of vaccinating children? *Multiple responses possible*	To protect them from diseases…(01) Does not have any benefit…(02) If other (specify)…(96) Not sure/Don't know…(99)	
603	Would you please mention childhood diseases that can be prevented by immunization? *Multiple responses possible* *probe: anything else?*	Tuberculosis…(01) Polio…(02) Diphtheria…(03) Pertussis…(04) Tetanus…(05) Measles…(06) Pneumonia…(07) Meningitis…(08) Hepatitis B…(09) Diarrheal Diseases…(10) Don't Know…(99) If other (specify)…(96)	If 602 = 01
604	What would be the disadvantages of vaccinating children? *Multiple responses possible*	Side or adverse effects…(01) May make them sick…(02) Takes time…(03) If other (specify)…(96) Not sure/Don't know…(99)	
605	How likely is it that your child will get a vaccine preventable disease if unvaccinated?	Very serious…(01) Somewhat serious…(02) Not serious at all…(03) Not sure/Don't know…(99)	
606	How serious would it be if your child got a vaccine preventable disease?	Very serious…(01) Somewhat serious…(02) Not serious at all…(03) Not sure/Don't know…(99)	
607	When do you think a child should start on immunization?	At birth…(01) First few weeks…(02) First few months…(03) Later…(04) Don't Know…(99)	
608	Where can you take a child to be vaccinated? *Multiple responses possible*	Outreach cites…(01) Health post…(02) Health centre…(03) Hospital…(04) Private clinic, hospital…(05) If other (specify)…(96) Don't know/not sure…(99)	
609	In the last 6 months have you received any information or message about vaccination to children?	Yes…(01) No…(02)	 > 612

610	What was your source of information? Or where did you get the information? *Multiple responses possible* *Probe: anyone else?*	Health professionals (doctors, nurses….)…(01) Health extension workers…(02) Volunteer community health workers…(03) Radio…(04) TV…(05) Newspaper, magazine…(06) Other printed materials (poster, banner) …(07) Husband/partner…(08) Family/friend/neighbor…(08) Religious/community leaders…(08) If other (specify)…(96) Don't know/not sure…(99)	
611	What messages have you heard about immunization? *Multiple responses possible* *Probe: anything else?*	Importance of vaccination…(01) About vaccination campaigns…(02) Where to get routine vaccination…(03) Timing for vaccination…(04) Return to next doses of vaccination…(05) Possible adverse events vaccination…(06) Harms of vaccination…(07) If other (specify)…(96) Don't know/not sure…(99)	
612	In the last 6 months, were you informed about possible adverse events (like mild fever) of vaccination?	Yes…(01) No…(02)	
613	Were you told what to do if your child experiences adverse effects (like mild fever) following vaccination?	Yes…(01) No…(02)	
614	Have you refused a vaccination offer by health worker for [NAME]?	Yes…(01) No…(02)	 > 616
615	If yes, why did you refuse?	Too many shoots at visit…(01) Child was ill…(02) Has already been vaccinated…(03) Fear of injection pain…(04) Fear of risk of disease transmission…(05) Fear of side effects…(06) Doubts on the benefit of the vaccine…(07) Did not trust the health worker…(08) If other (specify)…(96)	
616	Do you believe that there are some children who should not be vaccinated or might be hurt by vaccination?	Yes…(01) No…(02) Not sure…(99)	 > 618 > 618
617	Which children do you think should not receive vaccination? *Multiple responses possible*	Newborns…(01) Sick children…(02) Physically handicapped children…(03) If other (specify)…(96)	
618	Do you have any fear, doubts, suspicions about having [NANE] vaccinated?	Yes…(01) No…(02) Not sure…(99)	 > 620 > 620

619	Why doubts/suspicion/fear do you have about your child vaccination?	Vaccinations cause side effects…(01) Vaccinations can make children sick…(02) Vaccinations sterilize children…(03) If other (specify)…(96)	
620	Do you recommend children in your community like [NAME] to get vaccinated?	Yes…(01) No…(02) Not sure…(99)	> 622 > 622
621	Why don't you recommend other caregivers to get their children vaccinated? *Multiple responses possible*	Don't believe vaccines are useful…(01) Causes side effect/ make them sick…(02) Injection can transmit diseases…(03) It's against social/religious norm…(04) If other (specify)…(96)	
622	Are you satisfied with the vaccination service provision in your area?	Yes…(01) No…(02) Not sure…(99)	> 701 > 701
623	Why you are not satisfied with the vaccination service provided in your area? *Multiple responses possible* *Probe: anything else?*	Vaccination service not accessible…(01) Vaccination site closed/vaccinator absent …(02) No vaccine at the vaccination cite…(03) Long waiting time…(04) Vaccinator not friendly/has poor communication skill…(05) Vaccination site is dirty/not clean…(06) Vaccinator not willing to open multivial…(07) Vaccination is expensive…(10) If other (specify)…(96)	

Section VII: Child immunization history				
No	**Question and reminders**	**Choices or answer spaces**		**Skip**
701	Do you have a card or another document where [NAME]'s vaccinations are written down?	Yes, has card or another document…(01) No, no card or other document…(02)		 > 705
702	May I see the card or other document where [NAME]'s vaccinations are written down?	Yes, card or another document seen…(01) No, no card or other document seen…(02)		> 704 > 706
703	If not seen, why?	Does not want to show…(01) Kept in the health facility…(02) Missed…(03) Locked in another place…(04) If other (specify)…(96)		
704	*Data collector: copy the following information from the vaccination card or document Enter "99" if card/document shows that a dose was given, but no date is recorded.*			

	Vaccines			**Date given (dd/mm/yy)**	
A	BCG	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
B	Polio-0	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
C	Polio-1	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
D	Polio-2	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
E	Polio-3	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
F	Penta-1	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
G	Penta-2	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
H	Penta-3	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
I	PCV-1	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
J	PCV-2	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
K	PCV-3	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
L	Rota-1	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
M	Rota-2	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
N	Measles-1	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	
O	Measles-2	Yes…(01)	No…(02)	|__|__|/|__|__|/|__|__|	

705	I want to take the picture of [NAME]'s vaccination card or document so that it will help me to counter check the information I filled. Are you willing? *Data collector: if the caregiver consented take the snap short and upload the picture.*	Yes…(01) No…(02)	 >801
706	Did [NAME] ever receive any vaccinations to prevent [NAME] from getting diseases, including vaccinations received in campaigns or immunization or child health days?	Yes…(01) No…(02) Don't know/Not sure…(99)	 > 611 > 611
707	*Data collector: Ask the mother whether the child has received the following vaccinations or not*		
A	Has [NAME] ever received a BCG vaccination against tuberculosis, that is, an injection in the arm or shoulder that usually causes a scar?	Yes…(01) No…(02) Don't know/Not sure…(99)	
B	Has [NAME] ever received oral polio vaccine, that is, two drops in the mouth to prevent polio?	Yes…(01) No…(02)	

		Don’t know/Not sure…(99)	
C	Did [NAME] receive the first oral polio vaccine in the first two weeks after birth or later?	First two weeks…(01) Later…(02)	
D	How many times did [NAME] receive the oral polio vaccine?	|___| number of times	
E	Has [NAME] ever received a pentavalent vaccination, that is, an injection usually given on the left upper thigh sometimes at the same time as polio drops?	Yes…(01) No…(02) Don’t know/Not sure…(99)	
F	How many times did [NAME]receive the pentavalent vaccine?	|___| number of times	
G	Has [NAME] ever received a pneumococcal vaccination, that is, an injection usually given on the right upper thigh to prevent pneumonia?	Yes…(01) No…(02) Don’t know/Not sure…(99)	
H	How many times did [NAME] receive the pneumococcal vaccine?	|___| number of times	
I	Has [NAME] ever received a rotavirus vaccination, that is, liquid in the mouth to prevent diarrhea?	Yes…(01) No…(02) Don’t know/Not sure…(99)	
J	How many times did [NAME] receive the rotavirus vaccine?	|___| number of times	
K	Has [NAME] received the first measles vaccination, that is, an injection in the arm to prevent measles given at 9 months?	Yes…(01) No…(02) Don’t know/Not sure…(99)	
L	Has [NAME] received the second measles vaccination, that is, an injection in the arm to prevent measles given at 15 months?	Yes…(01) No…(02) Don’t know/Not sure…(99)	
708	Does [NAME] have a BCG scar at the left upper arm? *Check with your observation*	Yes…(01) No…(02) Not possible to observe…(99)	
709	In addition to what is recorded on the document or what I asked you before, did [NAME] receive any other vaccinations, including vaccinations received in campaigns or immunization days or child health days? *If “yes” probe for vaccinations and fill under 707*	Yes…(01) No…(02) Don’t know/Not sure…(99)	

710	*Data collector: If vaccination card or document is not available, visit the nearby health facility, access the medical record of the child and fill the following information. Enter “99” if card/document shows that a dose was given, but no date is recorded. Select “99” if the data is not accessible.*					
A	BCG	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
B	Polio-0	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
C	Polio-1	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
D	Polio-2	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
E	Polio-3	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
F	Penta-1	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
G	Penta-2	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
H	Penta-3	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	

I	PCV-1	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
J	PCV-2	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
K	PCV-3	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
L	Rota-1	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
M	Rota-2	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
N	Measles-1	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	
O	Measles-2	Yes (01)	No (02)	Data not accessible (99)	|__|__|/|__|__|/|__|__|	

Section VIII: Barriers and enables to vaccination

No	Question and reminders	Choices or answer spaces	Skip
801	From the information your provided me, your child is under vaccinated for his/her age. What makes it ***difficult*** for you to ensure that your child is vaccinated against all the vaccine preventable diseases? *Multiple responses possible* *probe: anything else?*	Absence of health facility in the locality/ Vaccination service not accessible…(01) Health workers did not come to the village…(02) Vaccination site closed/vaccinator absent …(03) No vaccine at the vaccination cite…(04) Long waiting time…(05) Vaccinator not friendly/poor relationship with the vaccinator…(06) Domestic workload…(07) Vaccination is of no use…(08) Vaccination hurts children/make them sick…(09) My husband discouraged me…(10) Others in the family/community discouraged me…(11) Cultural or religious norms or beliefs…(12) Fear of cost associated with vaccination…(10) If other (specify)…(96) Don't know/Not sure…(99)	
802	From the information your provided me, your child is adequately vaccinated for his/her age. What makes it ***easier*** for you to ensure that your child is vaccinated against all the vaccine preventable diseases? *Multiple responses possible* *probe: anything else?*	Proximity of health facility/outreach site…(01) Door to door campaigns…(02) Vaccinations are important for children …(03) My husband supported/encouraged me…(04) Community health workers' follow up…(05) Others supported/encouraged me…(04) It is normal to vaccinate children …(06) If other (specify)…(96) Don't know/Not sure…(99)	
803	Do most of the people around you approve of you vaccinating [NAME] every time needed?	Yes…(01) No…(02) Don't know/Not sure…(99)	
804	Who are the people that approve of you vaccinating your child?	Husband/partner…(01) Parents/ parents in laws…(02) Other family members…(03) Neighbors/peers…(04) Religious/community leaders…(05) If other (specify)…(96)	803=01
805	Who are the people that disapprove of you vaccinating your child?	Husband/partner…(01) Parents/ parents in laws…(02) Other family members…(03) Neighbors/peers…(04)	803=02

		Religious/community leaders…(05) If other (specify)…(96)		
806	How difficult would it be to get your child vaccinated? Very difficult, somewhat difficult, not difficult at all	Very difficult…(01) Somewhat difficult…(02) Not difficult at all…(03)		
807	How difficult was it to remember the vaccination schedule of [NANME]	Very difficult…(01) Somewhat difficult…(02) Not difficult at all…(03)		
808	Does your religion approve of vaccinating your child?	Yes…(01) No…(02) Don't know/Not sure…(99)		
809	Are there any cultural rules or taboos that you know of against vaccinating children?	Yes…(01) No…(02) Don't know/Not sure…(99)		
Section IX: Service integration				
No	**Question and reminders**	**Choices or answer spaces**		**Skip**
901	Late me take you to the time [NAME] was under the age of 1 year? During this time did you visit a health facility for any service?	Yes…(01) No…(02) Don't know/Not sure…(99)		
902	Why did you visit the health facility then? *Multiple responses possible* *probe: anything else?*	Antenatal or postnatal care…(01) Family planning…(02) Sick child care …(03) Growth monitoring…(04) To collect bed net…(05) Therapeutic or supplementary feeding program…(06) If other (specify)…(96) Don't remember/Not sure…(99)		
903	While you visited the health facility for the service, did the health worker asked you about the vaccination status of [Name]or encouraged you to vaccinate [Name]?			
A	Antenatal or postnatal care	Yes, at least once…(01)	No…(01)	902=01
B	Family planning	Yes, at least once…(01)	No…(01)	902=02
C	Sick child care	Yes, at least once…(01)	No…(01)	903=03
D	Growth monitoring	Yes, at least once…(01)	No…(01)	904=04
E	To collect bed net	Yes, at least once…(01)	No…(01)	905=05
F	Therapeutic/supplementary feeding program	Yes, at least once…(01)	No…(01)	906=06

Section X: Gender empowerment			
No	**Question and reminders**	**Choices or answer spaces**	**Skip**
1001	Who usually decides how the money you earn will be used: you, your (husband/partner), or you and your (husband/partner) jointly?	Respondent…(01) Jointly…(02) Husband/partner…(03) Has no earnings …(95) If other (specify)…(96)	211 = 02
1002	Who usually decides how your (husband/ partner's) earnings will be used: you, your (husband/partner), or you and your (husband/partner) jointly?	Respondent…(01) Jointly…(02) Husband/partner…(03) Husband/partner has no earnings …(95) If other (specify)…(96)	211 = 02
1003	Who usually makes decisions about making major household purchases?	Respondent…(01) Jointly…(02) Husband/partner…(03) Someone else …(95)	211 = 02
1004	Who usually makes decisions about health care for yourself: you, your (husband/ partner), you and your (husband/partner) jointly, or someone else?	Respondent…(01) Jointly…(02) Husband/partner…(03) Someone else …(95)	211 = 02
1005	Who usually makes decisions about health care for [name]: you, your (husband/partner), you and your (husband/partner) jointly, or someone else?	Respondent…(01) Jointly…(02) Husband/partner…(03) Someone else …(95)	211 = 02
1006	Who usually makes decisions about visits to your family or relatives?	Respondent…(01) Jointly…(02) Husband/partner…(03) Someone else …(95)	211 = 02
1007	Does your husband help you with household chores like caring and looking after children, cooking, cleaning the house and doing other work around the house?	Yes…(01) No…(02) Don't know/Not sure…(99)	211 = 02
1008	Does he help you almost every day, at least once a week or rarely?	Almost every day…(01) About once per week…(02) Rarely …(03)	1007 = 01
1009	Do you own this or any other house either alone or jointly with someone else?	Alone only…(01) Both alone and jointly…(02) Jointly only…(03) Does not own…(04)	211 = 02
1010	Do you own any agricultural or non-agricultural land either alone or jointly with someone else?	Alone only…(01) Both alone and jointly…(02) Jointly only…(03) Does not own…(04)	211 = 02
1011	In the last complete 24 hours (starting yesterday morning to today's morning, how many hours did you spend working?	|___|___| hours	211 = 02
1012	Who generates income for household consumption?	Respondent…(01) Husband/partner…(02) Both…(03) If other (specify)…(96)	

1013	Who allocates money for health expenses?	Respondent…(01) Husband/partner…(02) Both…(03) If other (specify)…(96)	
1014	Who saves money from the income generation activity?	Respondent…(01) Husband/partner…(02) Both…(03) If other (specify)…(96)	
1015	Does anyone of the family member have access to credit scheme?	Yes…(01) No…(02) Don't know…(03)	
1016	Who has access to the credit scheme in the community?	Alone only…(01) Both alone and jointly…(02) Jointly only…(03) Does not own…(04)	1015= 01
1017	Have your family ever approached by community representatives or government authorities to attend in different social and health related meetings?	Yes…(01) No…(02) Don't know…(03)	
1018	If yes, who usually attends the social and health related meetings organized by community representatives or government authorities?	Respondent…(01) Husband/partner…(02) Both…(03) If other (specify)…(96)	1017= 01
1019	Have you or any one of your family members ever taken training on health, reproductive health or immunizations organized by nearby health facilities?	Yes…(01) No…(02) Don't know…(03)	
1020	If yes who usually participate in the training?	Respondent…(01) Husband/partner…(02) Both…(03) If other (specify)…(96)	1019= 01
1021	any of you or your family have any representation as a committee member or leader in the community gathering, community-based organization, health committee or government structure?	Yes…(01) No…(02) Don't know…(03)	
1022	yes who usually have a role in the committee?	Respondent…(01) Husband/partner…(02) Both…(03)	1021 = 01

1023	Who has more access to information about what is happening in the community with regard to health updates and vaccination campaigns?	Respondent…(01) Husband/partner…(02) Both…(03)	
1024	Is there kind of family dialogue among your family members on free discussion about health issues including immunization?	Yes…(01) No…(02) Don't know…(03)	
1025	yes, who usually initiates the dialogue?	Respondent…(01) Husband/partner…(02) Both…(03) If other (specify)…(96)	1024 = 01
This is the end of our interview. Thank you very much for taking part in this interview.			

Section XI: Endnotes			
1101	Time the interview started *Local time, 12-hour clock (AM/PM)*	|___|___|: |___|___| |___|___|	
1102	GPS location	Latitude: _________________ Longitude: _________________ Altitude: _________________	
1103	Form completion status	Complete…(01) Incomplete…(02)	

APPENDIX 2

Ethiopian Public Health Institute

Institutional Review Board (EPHI-IRB)

Certificate of Approval

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Ethiopian Public Health Institute
አዲስ አበባ-ኢትዮጵያ Addis Ababa, Ethiopia

ስልክ-Tel: +251 11 2133499, +251 11 2751522, ፋክስ Fax: +251 11 2758634,
የፖ.ሳ.ቁ - P. O. BOX: 1242/5654 e-mail: ephi@ethionet.et
www.ephi.gov.et

ቁጥር Ref. No EPHI 6.13/810
ቀን Date 15-02-2022

Ethiopian Public Health Institute
Institutional Review Board (EPHI-IRB)
Certificate of Approval

Protocol number: **EPHI-IRB-416-2021**
Minutes No; 100

Protocol Title: Reaching Zero dose children for routine vaccines in underserved settings of Ethiopia; Evaluation		
Investigators:	Dr Samson Gebremedhin	
Institute:	Project HOPE	
Study site/s	Ethiopia	
Elements Reviewed (EPHI-IRB AF 01-008/02.0):	☐ Attached	✔ Not attached
Mode of Review	✔ Expedited	☐ Full Board
Decision of the meeting	✔ Approved	

I. Elements approved:
1. Protocol Version No: 02
2. Protocol Version Date: 29-01-2022
3. ICF Version No.; 02
4. ICF Version Date: 29-01-2022

II. . Obligations of the PI:
1. Should comply with the standard international &national scientific and ethical guidelines
2. All amendments and changes made in protocol and consent form needs IRB approval
3. The PI should report SAE within 48 hours of the event
4. This approval certificate is valid for only one year (specified below). The PI should Submit continuation request before expire date of approval, if projects is to continue
5. Final report/Thesis and Manuscripts should be submitted to the IRB secretariat after completion of the study.

Institutional Review Board Approval Date: February 5, 2022
Approval Period: From February 05, 2022 to February 04, 2023
Follow up report expected in:
6 months ____ 9 months ______one year ✔

EPHI-IRB Chairperson
Name Atkure Defar
Signature
Date: 08/02/22

EPHI Director General
Name
Signature
Date:

Getachew Tollera (Dr.)
Deputy Director General

The Federal Democratic Republic of Ethiopia
Ethiopian Public Health Institute