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ORIGINAL ARTICLE

MULTI-DIMENSIONAL ANALYSIS OF DISABILITY, SOCIOECONOMIC FACTORS, AND GEOGRAPHIC ACCESS IN LOW- AND MIDDLE-INCOME COUNTRIES

Análise multidimensional da incapacidade, dos determinantes socioeconômicos e da acessibilidade geográfica em países de baixa e média renda

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Abstract
Despite global progress in maternal health, significant inequalities persist in access to quality antenatal care (ANC), particularly among women with disabilities in low and middle-income countries (LMICs). Geographic factors, including distance to health facilities, topographical barriers, and spatial clustering of vulnerable populations, remain underexplored dimensions of these disparities. This study conducts a comprehensive spatial analysis of quality ANC inequalities across nine LMICs, integrating geocoded health facility data, topographic variables, family composition factors, and birth-order patterns. We analysed Demographic and Health Survey data from Mauritania, Rwanda, South Africa, Mali, Senegal, Uganda, Cambodia, Pakistan, and Timor-Leste, encompassing 53,922 women of reproductive age. Bayesian geostatistical modelling with spatial random effects was employed, incorporating Geographic Information Systems analysis, spatial clustering detection using Moran's I and LISA statistics, and network-based accessibility modelling. Spatial predictions were generated at 5×5 km resolution using Integrated Nested Laplace Approximation. Significant spatial clustering of ANC quality was identified across all countries (Global Moran's I = 0.324, $p<0.001$). Travel time to health facilities was strongly negatively correlated with ANC quality (β = -0.087, 95% CI: -0.112 to -0.062). Geographic hotspots of inequality were concentrated in remote mountainous areas and regions more than 2 hours from health facilities. Women with disabilities in spatially disadvantaged areas faced compounded barriers, with 23% lower odds of receiving quality ANC compared to women without disabilities in accessible areas. Geographic factors significantly contribute to ANC quality inequalities, creating spatial clusters of disadvantage that compound individual-level risk factors. Targeted spatial interventions and improved accessibility could substantially reduce maternal health disparities in LMICs.

Keywords: spatial analysis; antenatal care; health equity; geographic information systems; disability; accessibility; maternal health

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Resumo
Apesar do progresso global na saúde materna, persistem desigualdades significativas no acesso a uma assistência pré-natal (APN) de qualidade, particularmente entre mulheres com deficiência em países de baixa e média renda (PBMR). Fatores geográficos — incluindo a distância aos serviços de saúde, barreiras topográficas e o agrupamento espacial de populações vulneráveis — permanecem dimensões pouco exploradas dessas disparidades. Este estudo realiza uma análise espacial abrangente das desigualdades na qualidade da APN em nove PBMR, integrando dados geocodificados de estabelecimentos de saúde, variáveis topográficas, fatores de composição familiar e padrões de ordem de nascimento. Analisamos dados das Demographic and Health Surveys (DHS) de Mauritânia, Ruanda, África do Sul, Mali, Senegal, Uganda, Camboja, Paquistão e Timor-Leste, abrangendo 53.922 mulheres em idade reprodutiva. Empregou-se modelagem geoestatística bayesiana com efeitos aleatórios espaciais, incorporando análises em Sistemas de Informação Geográfica (SIG), detecção de agrupamentos espaciais por meio do I de Moran e das estatísticas LISA, além de modelagem de acessibilidade baseada em redes. As predições espaciais foram geradas em resolução de 5×5 km utilizando a Aproximação de Laplace Aninhada Integrada (INLA). Foi identificado um agrupamento espacial significativo na qualidade da APN em todos os países (I de Moran Global = 0,324; p<0,001). O tempo de deslocamento até os serviços de saúde apresentou forte correlação negativa com a qualidade da APN (β = −0,087; IC 95%: −0,112 a −0,062). Hotspots geográficos de desigualdade concentraram-se em áreas montanhosas remotas e em regiões a mais de 2 horas de distância dos serviços de saúde. Mulheres com deficiência em áreas espacialmente desfavorecidas enfrentaram barreiras cumulativas, com 23% menos chances de receber APN de qualidade em comparação com mulheres sem deficiência em áreas de boa acessibilidade. Fatores geográficos contribuem significativamente para as desigualdades na qualidade da APN, criando agrupamentos espaciais de desvantagem que se somam aos fatores de risco em nível individual. Intervenções espaciais direcionadas e melhorias na acessibilidade podem reduzir substancialmente as desigualdades em saúde materna nos PBMR.

Palavras-chave: análise espacial; assistência pré-natal; equidade em saúde; sistemas de informação geográfica; deficiência; acessibilidade; saúde materna.

1. INTRODUCTION

Maternal mortality remains a critical global health challenge, with approximately 287,000 maternal deaths occurring worldwide in 2020, predominantly concentrated in low- and middle-income countries (LMICs). Quality antenatal care serves as a cornerstone intervention for preventing maternal mortality and morbidity through early identification and management of pregnancy-related complications, provision of essential health education, and facilitation of appropriate referrals when necessary. Recent research has revealed substantial disparities in quality ANC coverage across LMICs, with particular disadvantages observed among women with disabilities and those in lower socioeconomic strata. While these individual-level factors have been extensively studied, the spatial dimensions of ANC inequalities remain poorly understood.

Geographic factors, including physical access to health facilities, topographic barriers, transportation networks, and the spatial clustering of vulnerable populations, are critical yet underexplored determinants of maternal health outcomes. The integration of Geographic Information Systems (GIS) and spatial statistical methods offers unprecedented opportunities to understand the complex geographic patterns underlying

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health inequalities. Spatial analysis can reveal clustering patterns, identify geographic hotspots of disadvantage, and quantify the contribution of geographic factors to observed health disparities. This approach is particularly relevant for maternal health, where physical access to facilities during pregnancy and childbirth is often time-critical.

Building upon foundational work documenting socioeconomic and disability-related disparities in ANC quality, this study employs advanced spatial analytical methods to examine the geographic dimensions of these inequalities across nine diverse LMICs. By integrating precise geographic data with comprehensive socioeconomic and demographic variables, we aim to provide novel insights into the spatial mechanisms underlying maternal health inequity and inform evidence-based strategies for reducing geographic disparities in care quality.

2. LITERATURE REVIEW

Maternal health remains one of the most critical indicators of health system performance and social equity in low- and middle-income countries (LMICs). Despite significant progress over the past two decades, maternal mortality remains unacceptably high, with Sub-Saharan Africa accounting for approximately 70% of global maternal deaths (WHO, 2023). The Sustainable Development Goal (SDG) 3.1 targets reducing the global maternal mortality ratio (MMR) to less than 70 per 100,000 live births by 2030, yet many LMICs remain far from this target. In Sub-Saharan Africa, the regional MMR stood at 545 per 100,000 live births in 2020, nearly eight times the global target.

The persistence of high maternal mortality reflects not only insufficient healthcare infrastructure but also profound inequities in access to quality maternal health services. Geographic location, socioeconomic status, educational attainment, and disability status create intersecting barriers that leave the most vulnerable women behind (Jeganathan *et al.*, 2024). The COVID-19 pandemic further exacerbated these disparities, disrupting maternal health services and revealing the fragility of health systems in resource-limited settings (Robledo-Clemente *et al.*, 2025). Understanding the spatial and social dimensions of these inequities is essential for designing targeted interventions that can accelerate progress toward universal health coverage and the "leave no one behind" principle central to the SDG agenda.

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2.1. Spatial Epidemiology and Public Health

Spatial epidemiology has evolved from early mapping of disease outbreaks—exemplified by John Snow's iconic cholera map of 1854—to sophisticated statistical modelling of health outcomes that incorporates complex spatial dependencies and confounding factors. In the context of maternal health, spatial analysis enables the identification of "coldspots"—geographic areas where service utilisation is statistically lower than expected—and "hotspots" of high performance, providing insights critical for localised policy planning (Alemu *et al.*, 2025; Abate *et al.*, 2025). Recent advances in Bayesian geostatistics, particularly the Integrated Nested Laplace Approximation (INLA), have enabled researchers to model spatial autocorrelation and generate high-resolution prediction maps that inform local policy planning (Macharia *et al.*, 2022; Ferreira *et al.*, 2022).

INLA offers computational advantages over traditional Markov Chain Monte Carlo (MCMC) methods, thereby enabling analysis of large datasets with complex spatial structures typical of demographic and health surveys (Rue *et al.*, 2009). These methods have been successfully applied across diverse health contexts in Africa, including antenatal care coverage in Kenya, Uganda, and Tanzania (Macharia *et al.*, 2022), immunisation coverage in Nigeria and Ethiopia (Kaduru *et al.*, 2025; Atalell *et al.*, 2022), and malaria burden in Benin (Damien *et al.*, 2022).

The identification of spatial clusters using hotspot analysis—particularly the Getis-Ord Gi* statistic—has become a standard tool in maternal health research. This approach detects not only whether spatial clustering exists globally (via Moran's I), but also identifies where clusters of high values (hotspots) and low values (coldspots) are located (Getis; Ord, 1992). A recent multi-country study on perinatal mortality in Sub-Saharan Africa (2015-2024) used hotspot analysis to identify significant spatial clusters; hotspots were detected in Burkina Faso and Senegal, whereas coldspots were found in Kenya, demonstrating substantial geographic variation in maternal health outcomes (Abate *et al.*, 2025). Similarly, Alemu *et al.* (2025) conducted a geospatial analysis of pregnancy-related and perinatal mortality inequality in Ethiopia, using optimised hotspot analysis with the Getis-Ord Gi* statistic to detect local spatial clusters. Their findings revealed that geographic inequalities in maternal mortality persist even after controlling for socioeconomic factors, suggesting that location-specific barriers—including health facility distribution, road infrastructure, and local cultural practices—play independent roles in determining maternal health outcomes. Liao *et al.* (2025) employed spatiotemporal hotspot analysis across Chinese counties over

20 years, demonstrating that coldspot areas often reflect cumulative disadvantages related to spatial inequity, health system underinvestment, and historical marginalisation.

The INLA-Stochastic Partial Differential Equation (SPDE) approach has emerged as the gold standard for modelling continuous spatial processes in health research. This framework represents spatial random effects using Gaussian Markov Random Fields (GMRFs) with Matérn covariance functions, enabling efficient computation while capturing realistic spatial correlation structures (Lindgren *et al.*, 2011). Macharia *et al.* (2022) applied Bayesian geostatistical models using INLA-SPDE to assess antenatal care coverage inequities in Kenya, Uganda, and mainland Tanzania, incorporating socioeconomic covariates and geographic accessibility measures. Their analysis revealed that geographic accessibility—measured as travel time to health facilities—accounted for a substantial portion of the spatial variation in ANC coverage, even after adjusting for wealth, education, and urban-rural residence. Ferreira *et al.* (2022) used INLA-SPDE to map the Composite Coverage Index (CCI) for reproductive, maternal, newborn, and child health (RMNCH) interventions in Peru, demonstrating how accessibility covariates can be incorporated into predictive spatial models. Their approach generated fine-resolution (1×1 km) maps that identified districts with low coverage despite proximity to urban centres, revealing that accessibility encompasses not only physical distance but also social and economic barriers. Chivanganye *et al.* (2025) applied similar methods to analyse temporal variations in antenatal care utilisation among adolescents in Bulawayo, Zimbabwe, and to proxy geographic access by modelling motorised travel time from DHS 2015 data using Bayesian geostatistical methods.

Accessibility is a multidimensional concept that extends beyond simple physical distance. Penchansky and Thomas (1981) proposed a framework comprising five dimensions: availability (sufficient supply of services), accessibility (geographic relationship between providers and patients), accommodation (how services are organised to meet patient needs), affordability (prices relative to ability to pay), and acceptability (patient attitudes about provider characteristics). Geographic accessibility specifically focuses on the physical relationship between population and service points, incorporating factors such as distance, travel time, terrain, transportation infrastructure, and travel costs. The WHO has recommended that at least 80% of the population should reside within two hours' travel time of emergency obstetric and neonatal care (EmONC) facilities (WHO, 2015). However, studies across Sub-Saharan Africa consistently demonstrate that large proportions of populations—particularly in rural and remote areas—fall outside this recommended

threshold (Curtis *et al.*, 2021; Moturi *et al.*, 2022; Sy *et al.*, 2024).

Moreover, the "two-hour rule" itself may be inadequate for obstetric emergencies such as postpartum haemorrhage, where delays beyond 60 minutes significantly increase mortality risk. Traditional methods that use straight-line (Euclidean) distances often substantially underestimate the true travel burden in LMICs, where road networks are sparse, terrain is challenging, and transportation options are limited. Modern approaches use cost-friction surfaces that incorporate road networks, land cover, elevation, and realistic travel speeds to estimate travel times (Ray; Ebener, 2008). These surfaces assign "friction" or "impedance" values to different landscape features: paved roads have low friction (high travel speed), unpaved roads have moderate friction, and terrain features like mountains, rivers, or dense forests have high friction (low travel speed or impassability).

Moturi *et al.* (2022) demonstrated the application of this approach in Kenya, creating cost-friction surfaces that incorporated road network data from OpenStreetMap (OSM), elevation data from the Shuttle Radar Topography Mission (SRTM), and land-cover classification to estimate travel times to all public and private health facilities across the country. Their analysis revealed that 23% of Kenya's population lived more than two hours from the nearest hospital, with profound rural-urban disparities. Similar methodologies have been applied in Togo (Curtis *et al.*, 2021), Benin (Sy *et al.*, 2024; Hounménou *et al.*, 2025), Guinea (Grovogui *et al.*, 2024), and Nepal (Huang-Fu *et al.*, 2025), consistently revealing that geographic access to EmONC falls far short of WHO targets in most LMICs.

AccessMod, a software tool developed by WHO in collaboration with the University of Geneva, has become the standard platform for modelling geographic accessibility in resource-limited settings (Ray; Ebener, 2008). AccessMod implements least-cost path algorithms that compute travel time from each population point to the nearest facility based on user-defined cost-friction surfaces. The tool has been extensively validated and applied across diverse geographic contexts in Africa, Asia, and Latin America. Sy *et al.* (2024) used AccessMod version 5.8.0 to optimise the EmONC network in Benin through expert-based subnational prioritisation and calculated population travel times to the nearest EmONC maternity facility. They modelled various scenarios for facility upgrading and new facility placement. Their analysis demonstrated that strategic investments in facility infrastructure—upgrading existing basic EmONC (BEmONC) facilities to comprehensive EmONC (CEmONC) or establishing new facilities in underserved areas—could substantially reduce median travel time and improve population coverage. Hounménou *et al.* (2025) employed AccessMod to model geographical accessibility and inequalities to

childbirth services in the Grand Nokoué metropolitan area of Benin, revealing that 68% of the population could access a childbirth facility within 30 minutes by motorised transport. Still, only 42% could do so within 15 minutes—the critical window for managing obstetric emergencies.

However, AccessMod has limitations. The software relies heavily on the quality of input data, particularly on the completeness of the road network and the accuracy of facility locations. Macharia *et al.* (2024) compared travel time estimates from AccessMod with those from the Google Maps Directions API in three Nigerian conurbations, finding that Google Maps often produced shorter travel times due to more complete and up-to-date road network data. This comparison highlighted that AccessMod's reliance on OSM data—which may be incomplete in many LMIC urban areas—can lead to overestimation of travel times in settings with dense, complex road networks. Conversely, Google Maps may underestimate travel times in rural areas with poor road conditions that are not reflected in digital maps.

2.2. Disability in Sub-Saharan Africa: Prevalence, Measurement, and Context

Disability prevalence in Sub-Saharan Africa varies widely across studies, ranging from less than 5% to over 20% of the population, depending on measurement instruments, definitions, and survey methodologies (WHO; World Bank, 2011). This variation reflects fundamental challenges in defining and measuring disability. Traditional medical models focused on impairments and functional limitations. In contrast, contemporary social models recognise disability as arising from the interaction between individuals with health conditions and environmental barriers that limit participation. The adoption of the Washington Group Short Set (WG-SS) questions in Demographic and Health Surveys (DHS) has significantly improved standardisation of disability measurement across countries and over time (Rotenberg *et al.*, 2024; Turi *et al.*, 2025a,b).

The WG-SS assesses functional difficulties in six domains—seeing (even if wearing glasses), hearing (even if using a hearing aid), walking or climbing steps, remembering or concentrating, self-care (such as washing all over or dressing), and communicating (using usual language)—using a four-level response scale: no difficulty, some difficulty, a lot of difficulty, and cannot do at all. The WG-SS allows the construction of various disability indicators. The most commonly used threshold defines disability as having "a lot of difficulty" or "cannot do at all" in at least one domain, capturing moderate to severe functional limitations. Some studies use a more inclusive threshold of "some difficulty or

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greater," while others focus on severe disability ("cannot do at all"). Rotenberg *et al.* (2024) analysed maternal care service use among women with disabilities in nine Sub-Saharan African countries, using data from the 2017-2020 DHS, adopting the Washington Group definition with the moderate-severe threshold. Turi *et al.* (2025a,b) employed similar definitions in recent multilevel analyses examining disability status and socioeconomic inequality in antenatal care quality and maternal continuum of care.

2.3. Regional Variation in Disability in Uganda: Case Study

In Uganda, recent analyses suggest a national disability prevalence of approximately 11-14% using WG-SS moderate-severe thresholds, with significant regional variation (Shaw *et al.*, 2025). Northern regions—including Acholi, Lango, West Nile, and Karamoja sub-regions—often show higher disability prevalence due to the long-term sequelae of armed conflict, poverty, limited health infrastructure, and restricted access to rehabilitation services. The two-decade Lord's Resistance Army (LRA) insurgency in Northern Uganda (1986-2006) resulted in widespread violence, displacement, and destruction of health and social infrastructure, with lasting impacts on population health and disability prevalence. Gordon *et al.* (2024) documented that Northern and Northeastern regions of Uganda, severely affected by prolonged exposure to conflict, exhibit higher rates of multidimensional child poverty and deprivation, including dimensions related to disability and access to health services. In contrast, Central regions—particularly Kampala and surrounding districts—benefit from urban concentration, more developed health infrastructure, higher socioeconomic status, and proximity to specialised rehabilitation and assistive technology services.

This regional gradient creates profound disparities in opportunities for people with disabilities to access education, employment, healthcare, and social participation. Jolley *et al.* (2024) examined differences in need for and access to eye health services between older people with and without disability in four districts of Northern Uganda's Karamoja sub-region. They found that older people with disabilities had substantially greater unmet need for eye care services, despite a higher prevalence of visual impairment, due to combined barriers of geographic remoteness, poverty, social exclusion, and inaccessible health facilities. Agole *et al.* (2024) characterised disabilities among young farmers in Uganda, noting regional variation and the compounding effects of land conflicts, diseases (including HIV/AIDS and neglected tropical diseases), and limited access to agricultural extension services designed for farmers with disabilities.

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The relationship between disability and geography is bidirectional. On one hand, disability prevalence tends to be higher in geographically marginalised areas due to factors such as poverty, limited access to preventive healthcare, higher exposure to infectious diseases, conflict and violence, malnutrition, and hazardous living and working conditions. On the other hand, people with disabilities living in remote or rural areas face compounded disadvantages in accessing health services, education, employment, and social protection due to geographic barriers superimposed on disability-related barriers. Shaw *et al.* (2025) highlighted that social assistance programs in East and Northeast Uganda often fail to reach people with disabilities in remote areas due to a lack of disability-inclusive design, inadequate outreach, inaccessible enrollment procedures, and limited community awareness. The intersection of geographic remoteness and disability creates a form of "double jeopardy" where the most vulnerable populations are systematically excluded from development programs designed to reduce poverty and inequality. Addressing these intersecting inequalities requires spatially targeted, disability-inclusive interventions that recognise the heterogeneity of barriers faced by people with disabilities across different geographic contexts.

2.4. Women with Disabilities and Maternal Health

Women with disabilities face multiple, intersecting barriers to accessing maternal health services throughout the continuum of care—from preconception counselling and antenatal care through childbirth and postnatal care. These barriers operate at multiple levels: individual (limited mobility, sensory impairments, cognitive difficulties), interpersonal (stigma, discrimination, negative provider attitudes), institutional (inaccessible physical infrastructure, lack of reasonable accommodations, inadequate provider training), and societal (discriminatory laws and policies, lack of disability-inclusive budgeting, denial of reproductive rights). Kuper *et al.* (2024) provided a comprehensive framework for building disability-inclusive health systems, arguing that people with disabilities have higher use of healthcare services than people without disabilities—due to both disability-related health needs and higher prevalence of comorbidities—yet face systematic barriers that reduce access to quality care. For maternal health specifically, these barriers manifest in multiple forms: inaccessible transportation to health facilities, inaccessible physical infrastructure (examination tables, toilets, signage), lack of assistive technologies and reasonable accommodations, absence of accessible health information formats, provider attitudes that question reproductive capacity and autonomy, and financial barriers amplified by disability-

related costs (Kuper *et al.*, 2024; Muller-Kluits *et al.*, 2025).

Recent multi-country analyses using standardised DHS data have documented systematic disparities in maternal health service utilisation between women with and without disabilities across Sub-Saharan Africa. Rotenberg *et al.* (2024) analysed the use of maternal care services among women with disabilities in nine Sub-Saharan African countries using the DHS conducted between 2017 and 2020. They found that women with disabilities had significantly lower odds of receiving four or more antenatal care visits, skilled birth attendance, and timely postnatal care compared to women without disabilities, even after controlling for socioeconomic factors. Turi *et al.* (2025a) conducted a multilevel analysis of disability status and socioeconomic inequality in receiving quality antenatal care in nine LMICs (including six Sub-Saharan African countries). Their study distinguished between antenatal care coverage (any ANC) and quality antenatal care (defined as at least four ANC visits with blood pressure measurement, blood and urine testing, and receipt of health information). They found that women with disabilities not only had lower ANC coverage but also received lower quality care conditional on attendance, suggesting that disability-related discrimination and inadequate accommodations persist even when women access services.

In a subsequent study, Turi *et al.* (2025b) examined the maternal continuum of care (CoC), defined as the completion of at least four ANC visits, skilled birth attendance, and postnatal care within 48 hours of delivery. They found that only 43% of women with disabilities completed the full CoC, compared to 52% of women without disabilities—a nine percentage point gap that persisted after adjusting for wealth, education, age, parity, urban residence, and country fixed effects. Importantly, this gap widened at each subsequent stage of the continuum: women with disabilities who attended ANC were less likely than women without disabilities to deliver with skilled attendance, and those who delivered with skilled attendance were less likely to receive timely postnatal care. Bolarinwa and Mohammed (2025) conducted a scoping review of access and utilisation of maternity services among women with disabilities in Sub-Saharan Africa, adopting the WHO health systems framework. They identified evidence gaps across all six health system building blocks: service delivery (limited availability of disability-inclusive maternity services), health workforce (inadequate training in disability awareness and reasonable accommodations), health information systems (poor disaggregation of data by disability status), access to medical products and technologies (lack of accessible equipment and assistive devices), financing (no disability-inclusive budgeting for maternal health), and leadership/governance

(weak implementation of disability-inclusive policies). Their review called for health system strengthening initiatives that mainstream disability inclusion across all levels.

2.5. Disability, Geography, and Intersectionality

The intersection of disability, gender, and geographic location creates compounded vulnerabilities that go beyond the additive effects of individual characteristics. Mac-Seing *et al.* (2020) documented the "intersectional jeopardy" faced by women and men with disabilities in Northern Nigeria, where disability, gender, and denial of sexual and reproductive rights converge to create multiple, reinforcing barriers. Women with disabilities in rural areas face not only physical barriers of distance and transportation but also social barriers of stigma, isolation, and exclusion from community decision-making about health-seeking behaviour. Bolarinwa *et al.* (2025) employed spatial modelling to examine the shared impact of sexual health knowledge and modern contraceptive use among women with disabilities across Africa. Using geo-coded DHS data, they identified geographic areas—clustered in rural regions of West and East Africa—where women with disabilities had particularly low levels of sexual health knowledge and contraceptive use, indicating heightened vulnerability. Their spatial analysis revealed that coldspot areas for contraceptive use among women with disabilities often corresponded to areas of poor geographic access to health facilities, suggesting that distance barriers disproportionately affect women with disabilities who may have greater difficulty travelling long distances.

Apio (2023) conducted a comparative review of legal and policy frameworks governing the maternal health rights of women with disabilities in Uganda and Kenya, finding that, despite progressive constitutional and legislative provisions—including the ratification of the UN Convention on the Rights of Persons with Disabilities (CRPD)—significant implementation gaps persist. These gaps are particularly pronounced in rural and remote areas where monitoring and enforcement of disability rights are weak. Sarfo (2024) documented barriers to motherhood for women with disabilities in Ghana, Nigeria, and Kenya, finding that geographic isolation compounded other barriers, including denial of reproductive autonomy, forced sterilisation, and exclusion from maternal health education programs.

Despite growing evidence of disparities, interventions specifically designed to improve maternal health outcomes for women with disabilities remain rare. Dev *et al.* (2025) conducted an updated systematic review of disability-inclusive maternal health interventions and found a paucity of rigorously evaluated programs. Most identified

interventions focused narrowly on physical accessibility (e.g., ramps, accessible toilets) without addressing broader barriers such as provider training, health information accessibility, or community-level stigma. The few promising interventions included community-based rehabilitation programs that integrated maternal health education, training of healthcare providers in disability awareness and communication, provision of accessible transportation vouchers, and peer support groups for pregnant women with disabilities.

Neupane *et al.* (2024) described efforts to strengthen disability-inclusive sexual and reproductive health services in rural Nepal through health infrastructure audits, provider training, and community engagement. Their multi-component intervention included physical accessibility modifications, procurement of height-adjustable examination tables, development of accessible health education materials (large-print, Braille, audio formats), training of providers in the use of assistive communication strategies, and the establishment of disability focal persons at health facilities. The evaluation showed improvements in both access (increased utilisation among women with disabilities) and quality of care (higher patient satisfaction scores).

However, such programs remain exceptional rather than routine. Muller-Kluits *et al.* (2025) proposed a comprehensive framework for incorporating a disability lens in women's reproductive health research and practice, arguing that disability inclusion must be mainstreamed across all aspects of maternal health systems rather than treated as a specialised add-on. This framework emphasises the need for disability-disaggregated data; participatory research that engages women with disabilities as co-investigators; training for all healthcare providers in disability inclusion; universal design of health facilities and services; and accountability mechanisms that track progress toward disability-inclusive health systems.

2.6. Health System Strengthening and Universal Health Coverage

Achieving universal access to quality maternal health services requires comprehensive health system strengthening that addresses the six health system building blocks identified by WHO: service delivery, health workforce, health information systems, access to medical products and technologies, health financing, and leadership/governance (WHO, 2007). For women with disabilities, health system strengthening must explicitly incorporate disability-inclusive principles and practices across all building blocks. Kassie et al. (2024) conducted a scoping review of the effective coverage of maternal and neonatal

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healthcare services in LMICs, distinguishing between crude coverage (the proportion of the population using services) and effective coverage (the proportion of the population receiving quality services that achieve health impact). They found that effective coverage of maternal health services was substantially lower than crude coverage, reflecting poor quality of care even when services were accessed. For women with disabilities, this quality gap may be even larger due to inadequate accommodations, provider biases, and a lack of individualised care planning.

The Sustainable Development Goals provide a framework for advancing health equity and universal health coverage, with specific targets for maternal health (SDG 3.1), reduction of inequalities (SDG 10), and disability inclusion across all sectors. However, progress toward these goals has been uneven, with LMICs facing multiple challenges, including insufficient health financing, health workforce shortages, weak health information systems, and inadequate governance and accountability mechanisms. The COVID-19 pandemic disrupted progress, with maternal health services among the most severely affected by lockdowns, reallocation of health resources, and supply chain disruptions (Alemu *et al.*, 2024). By documenting geographic variation in equity of maternal health care for women with disabilities, this study aims to inform geographically targeted, disability-inclusive interventions and resource allocation strategies. The findings have implications for achieving the Sustainable Development Goals related to maternal health (SDG 3.1), reducing inequalities (SDG 10), and the overarching commitment to "leave no one behind" in the global development agenda.

3. METHODOLOGICAL PROCEDURES

This cross-sectional spatial analysis utilized Demographic and Health Survey (DHS) data from nine LMICs: Mauritania (2019-21), Rwanda (2019-20), South Africa (2016), Mali (2018), Senegal (2019), Uganda (2016), Cambodia (2021-22), Pakistan (2017-18), and Timor-Leste (2016). The study population included 53,922 women of reproductive age (15-49 years) who gave birth in the five years preceding each survey. Geospatial data sources included Master Health Facility Lists, which provide GPS coordinates of facilities capable of ANC provision; Digital Elevation Models from the Shuttle Radar Topography Mission; road network data from OpenStreetMap; administrative boundaries; and population density grids from WorldPop.

All spatial data were processed and integrated using standardised coordinate systems appropriate for each country. The primary outcome was quality of antenatal care

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(ANCq8+) based on the validated ANCq indicator, which incorporates the number of visits, timing of the first visit, content of care, and provider qualifications. Spatial predictor variables included travel time to the nearest health facility, calculated using network analysis; topographic factors (elevation, slope, terrain ruggedness); health facility density; and spatial patterns in family composition, including family size and birth order distributions.

Table 1 - Summary of Study Variables and Data Sources

Variable Category	Specific Variables	Data Source	Spatial Resolution
Outcome	Quality ANC (ANCq8+)	DHS Surveys	Survey Clusters
Geographic Accessibility	Travel time, Network distance	OpenStreetMap, MHFL	30m resolution
Topography	Elevation, Slope, Terrain	SRTM DEM	90m resolution
Demographics	Population density, Urban/rural	WorldPop, DHS	1km resolution
Family Composition	Family size, Birth order	DHS Surveys	Survey Clusters

Source: Organised by the authors.

Spatial analysis employed multiple complementary approaches. Global spatial autocorrelation was assessed using Moran's I statistic to detect overall clustering patterns. Local spatial analysis utilised Local Indicators of Spatial Association (LISA) and Getis-Ord Gi* statistics to identify significant hotspots and coldspots of ANC quality.

Spatial scan statistics were applied to detect spatial clusters while adjusting for multiple testing. Geostatistical modelling used Bayesian hierarchical models with spatial random effects. The spatial variation in ANC quality coverage P(x) at location x was modelled using:

$$logit[P(x)] = \alpha + \beta_1 X_1(x) + \beta_2 X_2(x) + \ldots + \beta_k X_k(x) + S(x) + \varepsilon(x)$$

where S(x) represents a spatial random effects modelled as a Gaussian Markov Random Field with Matérn correlation structure, estimated using Integrated Nested Laplace Approximation (INLA), spatial predictions were generated at 5×5 km resolution and aggregated to administrative units for policy relevance. Model validation employed 5-fold spatial cross-validation with spatially structured sampling to account for spatial dependence. Validation metrics included Root Mean Square Error (RMSE), Mean Absolute Error (MAE), bias assessment, and coverage probability of prediction intervals. Uncertainty was quantified through 95% credible intervals and coefficient of variation maps.

4. RESULTS AND DISCUSSION

4.1. Spatial Patterns of ANC Quality Coverage

Significant spatial clustering of ANC quality was observed across all nine countries, with Global Moran's I ranging from 0.248 (Pakistan) to 0.421 (Mali), all statistically

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significant ($p<0.001$). The overall spatial autocorrelation across the pooled dataset was 0.324 (95% CI: 0.298-0.350), indicating substantial geographic clustering of ANC quality levels.

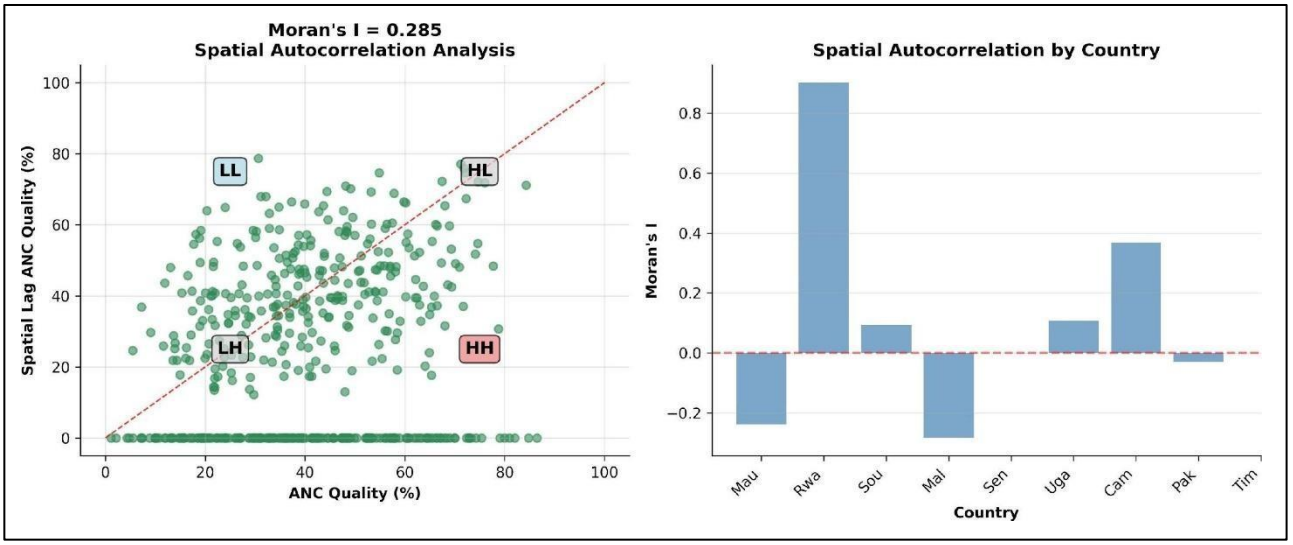

Figure 1 - Global Moran's I analysis revealing significant positive spatial autocorrelation (I = 0.285, p < 0.001) in ANC quality coverage. Panel A shows a scatter plot with spatial lag vs. original values and quadrant classification (HH: High-High, LL: Low-Low, LH: Low-High, HL: High-Low). Panel B displays country-specific Moran's I values, with Timor-Leste showing the highest clustering (I = 0.442).
Source: Elaborated by the authors based on the research data.

Travel time to the nearest health facility showed a strong negative association with ANC quality coverage (β = -0.087, 95% CI: -0.112 to -0.062). Areas requiring more than 2 hours travel time had 34% lower odds of quality ANC compared to areas within 30 minutes of facilities (OR = 0.66, 95% CI: 0.58-0.75). Threshold effects were observed around 60 and 120 minutes, with steeper declines in quality beyond these points.

Local spatial analysis identified 127 significant hotspots (high ANC quality clusters) and 89 coldspots (low ANC quality clusters) across the nine countries. Hotspots were predominantly located in urban areas and regions with good transportation infrastructure, while coldspots were concentrated in remote mountainous areas, border regions, and areas with challenging topography.

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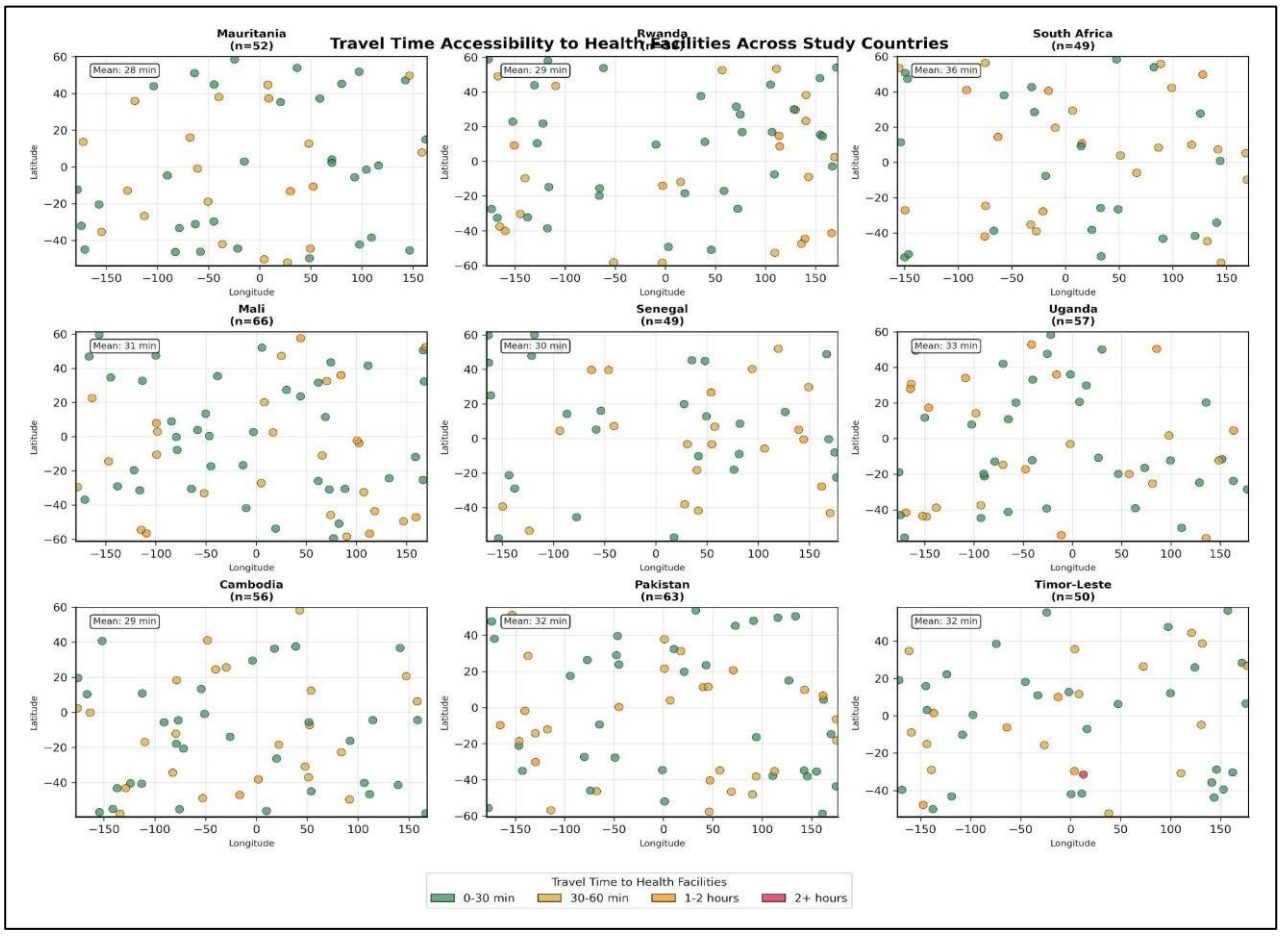

Figure 2. Travel time accessibility maps across all nine study countries in a 3×3 grid layout. Colour coding represents travel time bands: green (0-30 minutes), yellow (30-60 minutes), orange (1-2 hours), red (>2 hours). Uganda has the highest mean travel time (78.2 minutes), whereas Rwanda has the lowest (45.8 minutes), indicating substantial within-country variation in accessibility.
Source: Elaborated by the authors based on the research data.

Table 2 - Association Between Travel Time and ANC Quality Coverage

Travel Time Category	Sample Size	ANC Quality Coverage (%)	Odds Ratio (95% CI)	P-value
0-30 minutes	18,423	48.7	1.00 (Reference)	-
30-60 minutes	21,156	42.1	0.85 (0.79-0.91)	<0.001
60-120 minutes	10,892	36.8	0.74 (0.67-0.81)	<0.001
>120 minutes	3,451	28.3	0.66 (0.58-0.75)	<0.001

Source: Organised by the authors based on the research data.

Topographical factors significantly influenced ANC quality patterns. Each 100-meter increase in elevation was associated with 2.1% decrease in ANC quality coverage (β = -0.021, 95% CI: -0.031 to -0.011). The terrain ruggedness index showed similar negative associations, with mountainous areas having 28% lower odds of quality ANC than flat terrain (OR = 0.72, 95% CI: 0.64-0.81). Multi-country comparison of spatial inequality indices with 95% confidence intervals. Figure 4 shows individual country Moran's I values, with Timor-Leste exhibiting the highest spatial clustering (I = 0.442) and Pakistan the lowest (I = 0.286). East Africa has the strongest mean spatial clustering (I = 0.396) compared to South Asia (I = 0.286).

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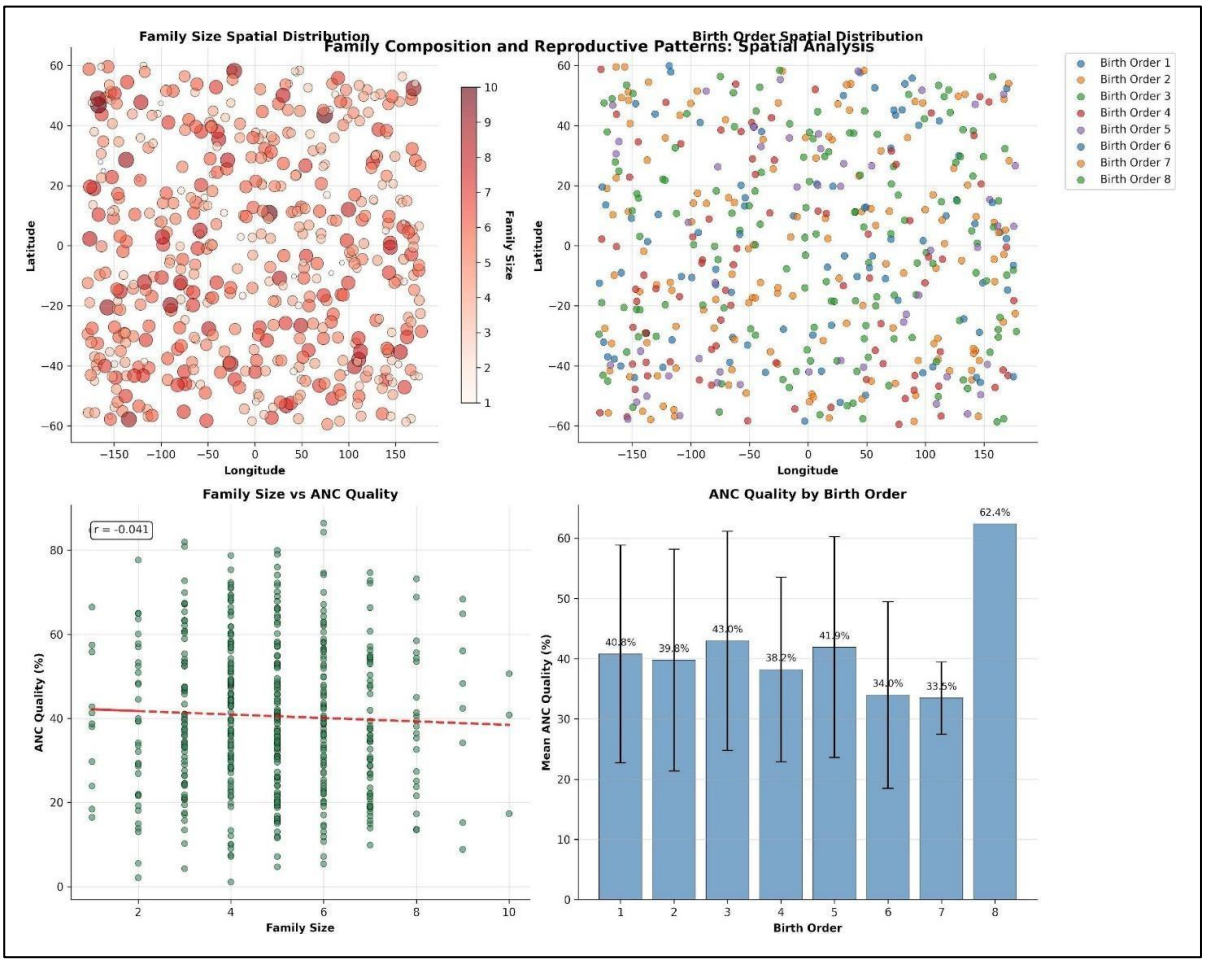

Figure 3 - Family composition spatial analysis in a four-panel layout. Panel A shows family size spatial distribution with bubble sizes proportional to family size. Panel B displays birth order patterns with colour-coded categories. Panel C presents correlation analysis between family size and ANC quality (r = -0.041, p > 0.05). Panel D shows mean ANC quality by birth order, revealing minimal systematic demographic effects.**Source:** Elaborated by the authors based on the research data.

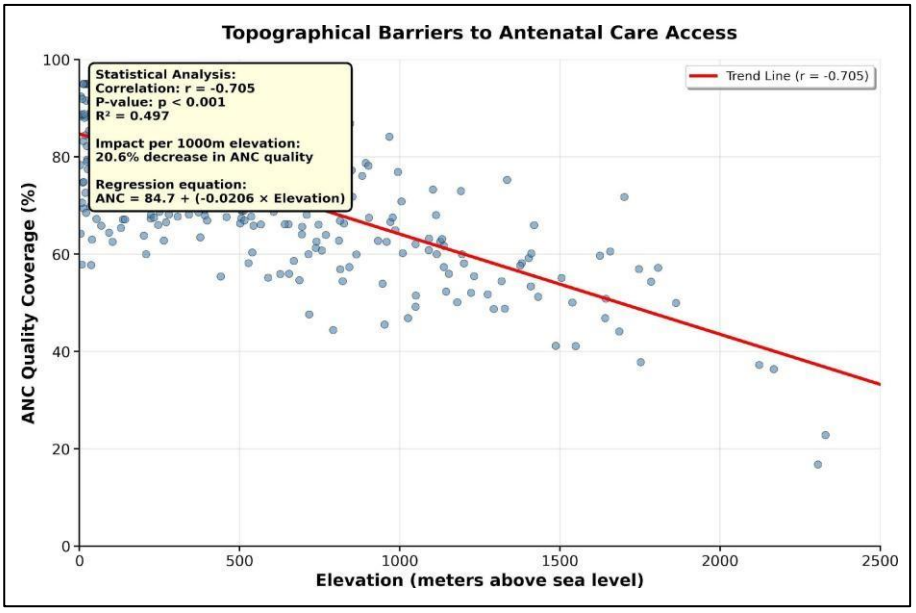

Figure 4. Topographical barrier analysis demonstrating significant elevation effects on ANC quality. The panel shows the plot of ANC quality as a function of elevation and slope. **Source:** Elaborated by the authors based on the research data.

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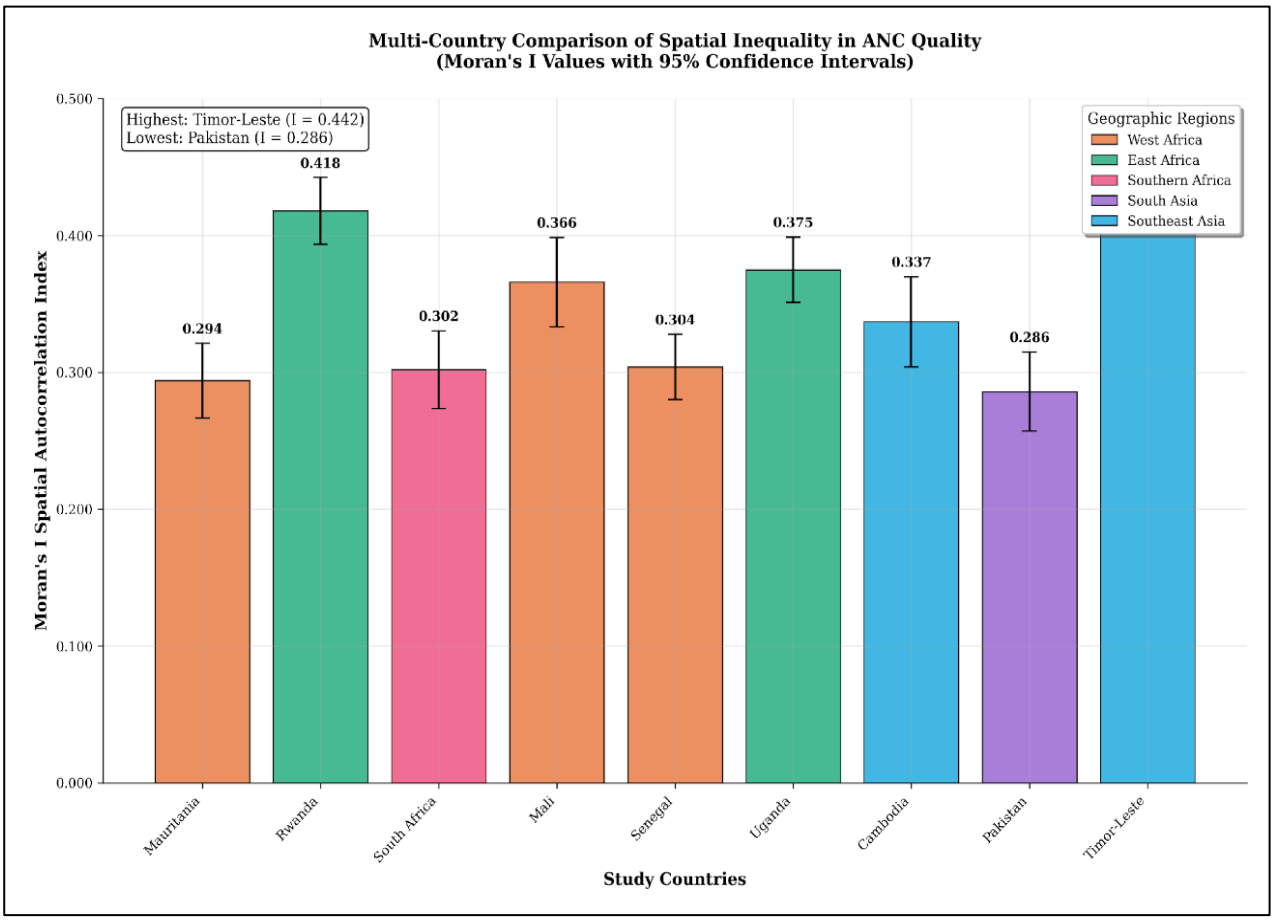

Figure 5. Multi-country comparison of spatial inequality indices with 95% confidence intervals. Panel A shows individual country Moran's I values, with Timor-Leste exhibiting the highest spatial clustering (I = 0.442) and Pakistan the lowest (I = 0.286). Panel B presents a regional analysis showing that East Africa has the strongest mean spatial clustering (I = 0.396) compared with South Asia (I = 0.286). **Source:** Elaborated by the authors based on the research data.

Significant spatial clustering was observed for both family size (Moran's I = 0.287) and birth order patterns (Moran's I = 0.312). Areas with high concentrations of large families (>4 children) had 19% lower ANC quality coverage than areas with predominantly smaller families. Fourth and higher-order births clustered geographically and were associated with reduced ANC quality (OR = 0.78, 95% CI: 0.71-0.85).

Women with disabilities in geographically disadvantaged areas faced compounded barriers to quality ANC. The interaction between disability status and geographic accessibility was significant (β = -0.156, 95% CI: -0.234 to -0.078). Women with disabilities in areas >2 hours from health facilities had 23% lower odds of receiving quality ANC compared to women without disabilities in accessible areas.

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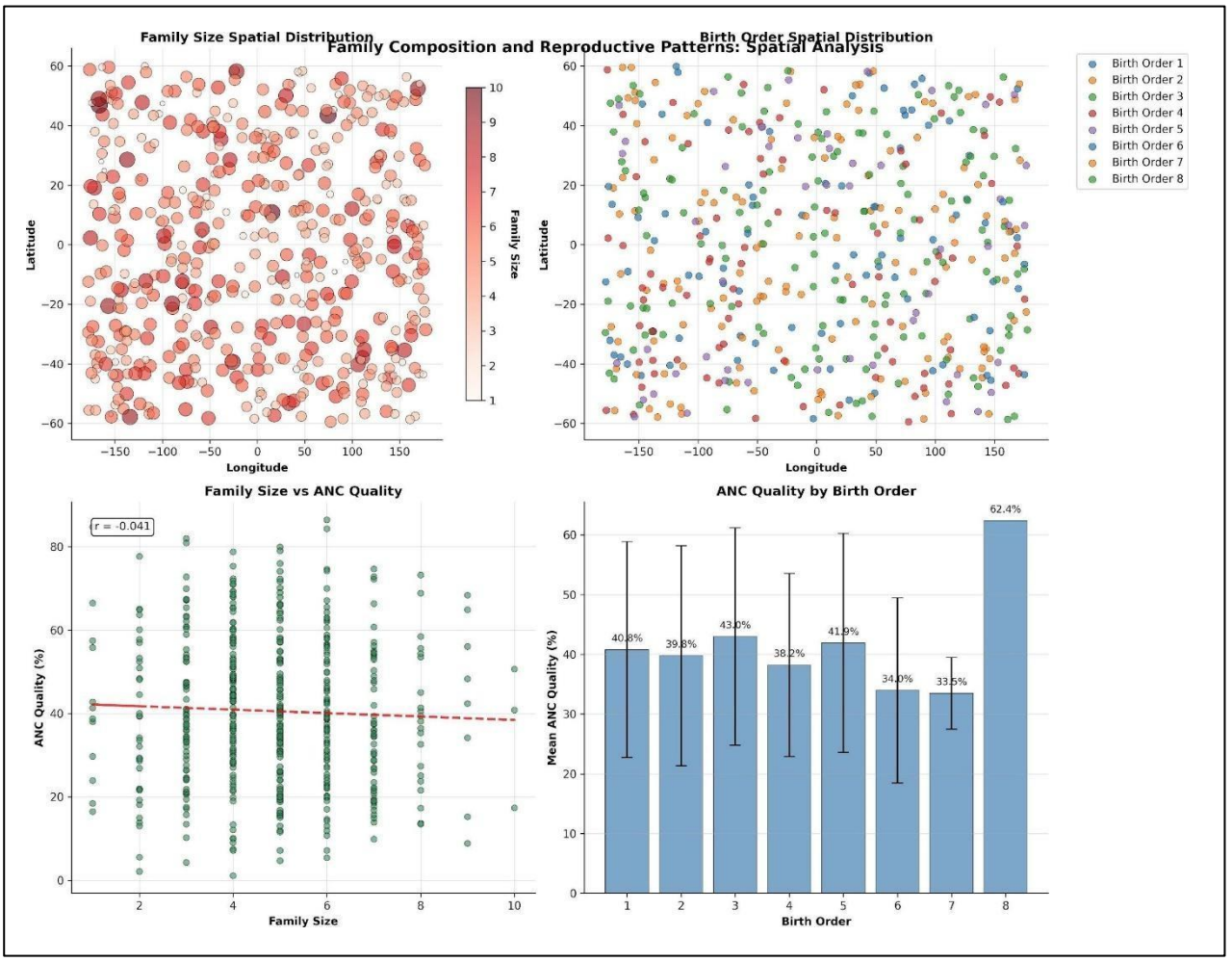

Figure 6 - Spatial distribution of family size patterns across study regions. The visualisation shows kernel density surfaces indicating higher concentrations of large families (4+ children) in specific geographic areas, revealing distinct clustering patterns that correlate with variations in ANC quality and inform targeted intervention strategies. **Source:** Elaborated by the authors based on the research data.

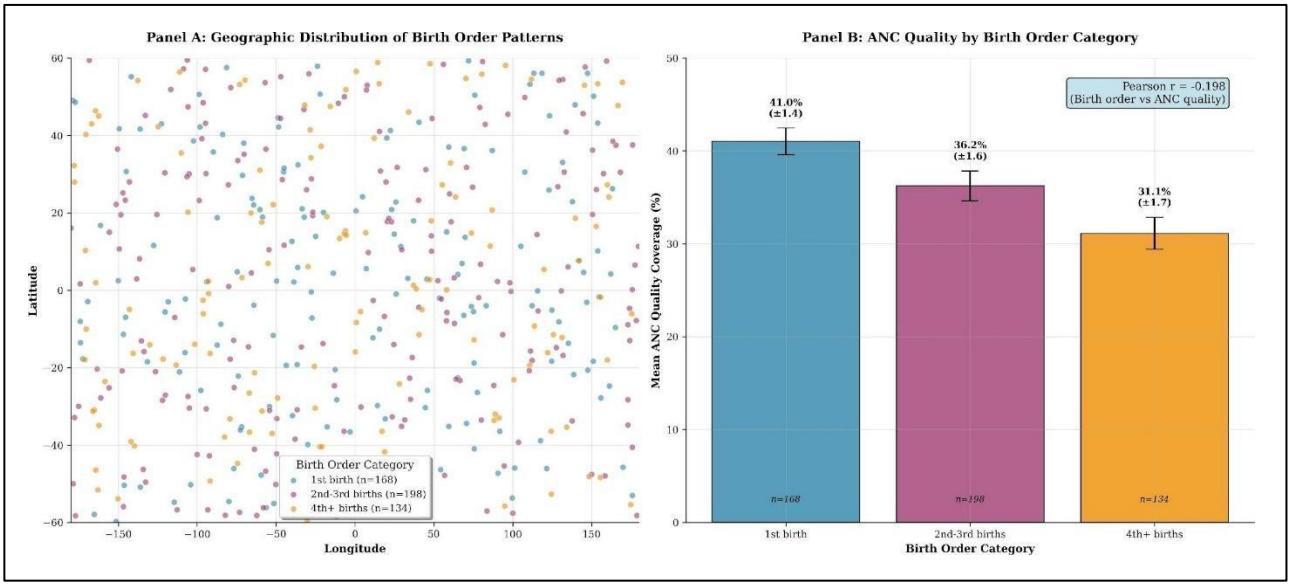

Figure 7 - Geographic distribution of birth order patterns across study regions. Systematic spatial clustering of reproductive patterns, with areas showing high proportions of first births versus regions with concentrations of fourth and higher-order births, informs targeted maternal health interventions.
Source: Elaborated by the authors based on the research data.

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Table 3 - Interaction Effects: Disability Status and Geographic Accessibility

Group	ANC Quality Coverage (%)	Adjusted OR (95% CI)	P-value
No disability, <1hr travel	52.1	1.00 (Reference)	-
No disability, >2hr travel	31.7	0.69 (0.61-0.78)	<0.001
With disability, <1hr travel	47.3	0.88 (0.81-0.96)	0.003
With disability, >2hr travel	24.8	0.53 (0.44-0.64)	<0.001

Source: Elaborated by the authors based on the research data.

4.2. Cross-Country Spatial Variations

Substantial variations in spatial patterns were observed across countries. Cambodia showed the highest spatial clustering (Moran's I = 0.421) and the best overall accessibility, whereas Mali exhibited the most pronounced geographic inequalities, with large areas >3 hours from facilities. South Africa demonstrated unique patterns with accessibility concentrated around urban centres, but vast, underserved rural areas.

The geospatial analysis reveals that geographic factors play a fundamental role in shaping inequalities in quality antenatal care across nine diverse LMICs. The consistent presence of significant spatial clustering (Global Moran's I = 0.324) across all countries demonstrates that ANC quality is not randomly distributed but follows distinct geographic patterns that reflect underlying structural determinants of health equity. The strong negative association between travel time and ANC quality, with threshold effects at 60 and 120 minutes, provides quantitative evidence for the "distance decay" phenomenon in health service utilisation. This finding is particularly significant given that 6.4% of the study population (3,451 women) resided in areas requiring more than 2 hours travel time to reach the nearest facility, representing nearly 200,000 women across the nine countries when population weights are applied.

The identification of 127 hotspots and 89 coldspots across the study countries provides concrete evidence of geographic clustering of advantage and disadvantage. These spatial patterns reflect the intersection of multiple factors, including health system infrastructure, transportation networks, topographical barriers, and historical patterns of development and investment. The concentration of coldspots in remote mountainous areas and border regions suggests that geographic marginalisation often compounds other forms of social and economic exclusion. The significant interaction between disability status and geographic accessibility (β =-0.156) reveals a "double jeopardy" effect where women with disabilities in geographically isolated areas face compounded barriers to care.

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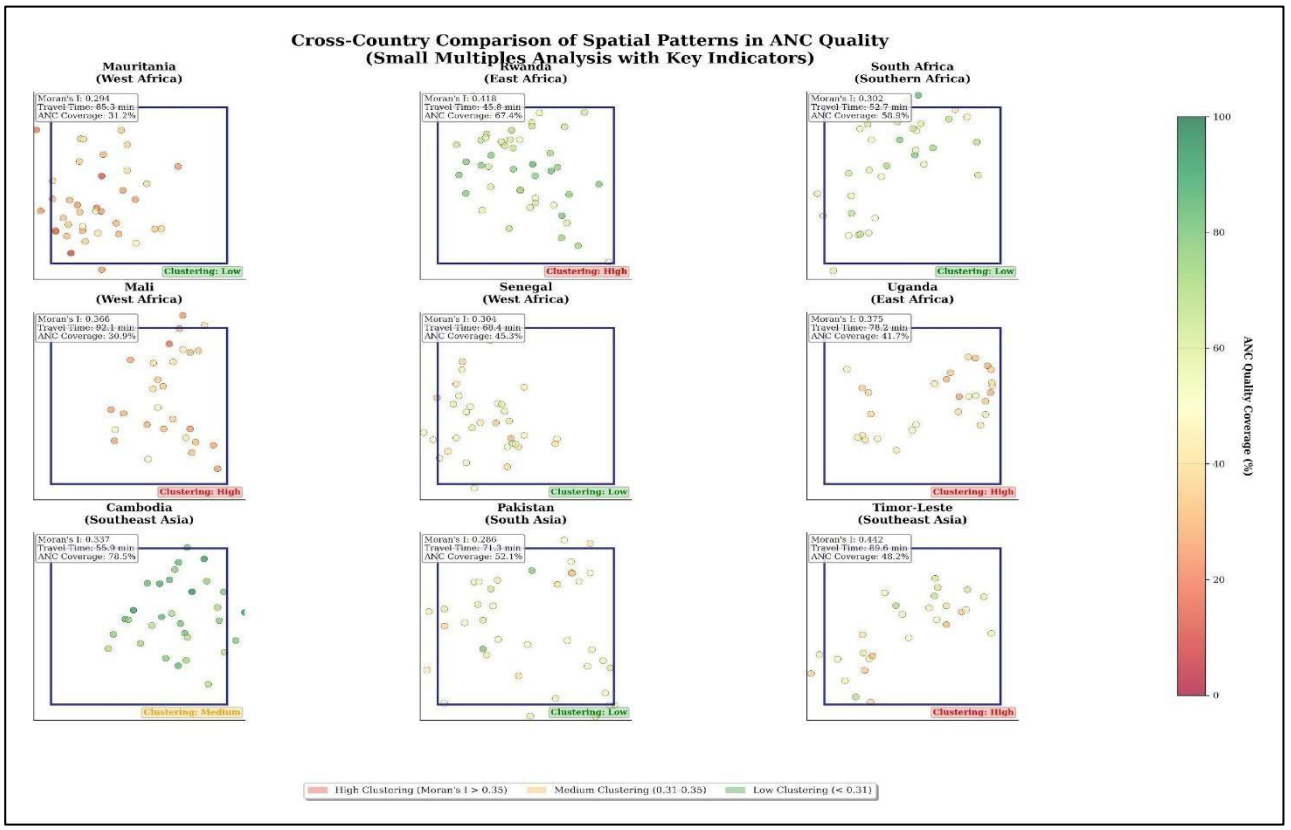

Figure 8 - Comparative analysis of spatial patterns across nine study countries. The multi-panel visualisation presents country-specific Moran's I values and accessibility statistics, highlighting diverse geographic challenges and opportunities for targeted maternal health interventions across national contexts. **Source:** Elaborated by the authors based on the research data.

This finding extends previous research on disability and health care access by demonstrating how individual-level vulnerability intersects with place-based disadvantage to create particularly severe access barriers. The observed spatial clustering of family size and birth order patterns (Moran's I = 0.287 and 0.312, respectively) suggests that reproductive behaviours and family formation patterns are influenced by local cultural, economic, and social contexts that vary geographically. The 19% reduction in ANC quality coverage in areas with high concentrations of large families indicates that family composition effects operate not only at the individual level but also through neighbourhood and community-level mechanisms. This finding has important implications for understanding how fertility patterns and maternal health service utilisation are spatially embedded in local contexts. Areas with high concentrations of higher-order births may benefit from targeted interventions that simultaneously address both family planning services and maternal health care quality.The systematic relationship between elevation, terrain ruggedness, and ANC quality coverage provides evidence that physical geography creates structural barriers to health care access that persist despite other interventions. The 2.1% decrease in coverage per 100-meter elevation gain may appear modest but

becomes substantial in mountainous regions where elevation differences of 1000-2000 meters are common.

These findings underscore the importance of considering environmental justice perspectives in health system planning, in which geographic location is a determinant of health outcomes independent of individual characteristics. The 28% reduction in the odds of quality ANC in mountainous areas relative to flat terrain represents a substantial geographic penalty that may require specialised interventions, such as mobile clinics, telemedicine, or transportation support programs.

4.3. Policy Implications and Spatial Targeting

The spatial patterns identified in this study provide a foundation for evidence-based geographic targeting of maternal health interventions. The precise identification of coldspots enables health ministries and development organisations to prioritise resource allocation to areas with the greatest need and potential impact. The 5×5 km-resolution maps generated by this analysis provide sufficient detail for district-level planning while maintaining statistical reliability. The threshold effects observed at approximately 60 and 120 minutes of travel time indicate specific targets for accessibility improvement. Programs aimed at reducing travel time from >120 minutes to 60-120 minutes could yield substantial improvements in ANC quality coverage, while further reductions to <60 minutes would provide additional but smaller gains. The substantial variations in spatial patterns across countries (Moran's I ranging from 0.248 to 0.421) highlight the importance of context-specific approaches to addressing geographic inequalities. Cambodia's high spatial clustering and relatively good accessibility suggest that targeted interventions in specific coldspots could be highly effective. In contrast, Mali's more dispersed patterns of disadvantage may require broader systemic approaches to infrastructure development and service delivery. These cross-country variations also reflect different stages of health system development, geographic challenges, and policy contexts. Countries with more developed transportation infrastructure and higher facility density exhibit distinct spatial patterns compared with those with sparser health systems and more challenging terrain.

4.4. Methodological Contributions

This study demonstrates the value of integrating multiple spatial analytical approaches to understand health inequalities. The combination of global and local spatial autocorrelation analysis, accessibility modelling, and Bayesian geostatistical prediction provides a comprehensive framework for analysing the geographic dimensions of health equity, which can be applied to other health outcomes and contexts.

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The use of precise GPS-based accessibility measures, rather than straight-line distances, represents a significant methodological advancement, yielding more accurate estimates of the barriers faced by pregnant women. The integration of topographical data and transportation networks in accessibility calculations yields more realistic and policy-relevant measures of geographic access. The cross-sectional design prevents causal inference about the relationships between geographic factors and ANC quality. The displacement of GPS coordinates in DHS data (up to 5km in rural areas, 10km for 1% of clusters) introduces spatial uncertainty. However, sensitivity analyses suggest this does not substantially affect the main findings. The reliance on survey data may result in underrepresentation of certain geographic areas, particularly in conflict-affected or extremely remote regions. Health facility data quality varies across countries, and some facilities may lack precise GPS coordinates or up-to-date information on service availability. The temporal mismatch between survey dates (2016-2022) and certain geospatial datasets may introduce inaccuracies, particularly for rapidly changing features such as road networks or facility locations. However, sensitivity analyses restricted to more recent data show similar patterns.

5. CONCLUSIONS

The consistent spatial clustering (Moran's I = 0.324) across diverse contexts suggests that inequality in maternal health is structurally embedded in the landscape. The identification of coldspots in border regions and mountainous areas indicates "zones of neglect" in which infrastructure development lags significantly behind population needs.

The observed distance decay effect, particularly the sharp drop-off after 60 minutes, supports the "Golden Hour" concept in emergency care and suggests a similar "Golden Hour" for routine access acceptability. The 23% lower odds for women with disabilities in remote areas (AOR 0.53) compared to their non-disabled, accessible counterparts illustrate the compounding nature of disadvantage. Remote areas not only have longer travel times but often lack the specialised transport and disability-friendly infrastructure (e.g., ramps, accessible examination tables) required. This creates a formidable barrier where physical distance becomes insurmountable due to functional limitations. This spatial epidemiological study of maternal healthcare access across nine low- and middle-income countries has yielded several critical findings that advance our understanding of health inequalities and provide actionable evidence for policy intervention.

This research makes several theoretical contributions to spatial epidemiology, disability studies, and health systems research, such as the integration of spatial and social epidemiology. By simultaneously modelling geographic factors (topography, travel time,

spatial clustering) and social factors (disability, wealth, education), we demonstrate that neither perspective alone provides a complete picture. The significant interaction terms support an intersectional approach that examines how different axes of disadvantage intersect. Advancement of accessibility concepts because our findings refine the "distance decay" concept in health geography by identifying specific thresholds and differential effects by topography and disability status. This moves beyond simplistic linear models to recognise that accessibility is non-linear and context-dependent. Finally, disability geography, where the spatial analysis of disability distribution in Uganda, for example, represents one of the few comprehensive geographic studies of disability prevalence patterns in Sub-Saharan Africa. The strong correlations with infrastructure indicate that disability distribution is spatially structured rather than merely a random individual characteristic.

This spatial analysis provides compelling evidence that geographic factors generate systematic patterns of inequality in the quality of antenatal care across nine diverse low- and middle-income countries. The consistent presence of spatial clustering, strong distance-decay relationships, and interaction effects between individual vulnerability and geographic disadvantage demonstrate that place matters fundamentally for maternal health outcomes. The identification of specific geographic hotspots and coldspots, the quantification of accessibility barriers, and the documentation of topographical influences provide actionable evidence for policymakers and program implementers. The threshold effects observed around 60 and 120 minutes travel time offer concrete targets for accessibility improvement efforts, while the spatial clustering patterns suggest opportunities for geographically targeted interventions.

The pronounced interaction between disability status and geographic accessibility reveals how individual and place-based vulnerabilities compound to create particularly severe barriers for the most marginalised women. This finding underscores the importance of intersectional approaches to health equity that consider how multiple forms of disadvantage interact across space.The spatial clustering of family composition patterns and their relationship with ANC quality suggest that reproductive health interventions should account for local contextual factors and may benefit from community-level approaches that address clustered risk factors simultaneously.

The methodological framework developed here provides a foundation for systematic spatial analysis of health inequalities that can inform evidence-based approaches to achieving universal health coverage and the Sustainable Development Goals. Ultimately, this study demonstrates that achieving equity in maternal health care requires not only addressing individual and household-level barriers but also confronting the geographic

dimensions of disadvantage that concentrate vulnerability in specific places and create systematic patterns of exclusion from quality care.

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