Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Spatial Heterogeneity in Minimum Acceptable Diet Among Children Aged 6–23 Months in India: Evidence from the National Family Health Survey,2019-21

Rakhi Bharati
International Institute for Population Sciences
Manas Ranjan Pradhan
International Institute for Population Sciences
Sumit Narayan Dwivedi
sumitnarayandwivedi28@gmail.com

International Institute for Population Sciences

Research Article

Keywords: Minimum acceptable diet, complementary feeding, child nutrition, spatial heterogeneity, multiscale geographically weighted regression, India

Posted Date: September 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10176241/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Background

Minimum acceptable diet (MAD), a composite indicator of minimum dietary diversity and minimum meal frequency, is essential for optimal growth and development during the first two years of life. Despite ongoing improvements in maternal and child health programmes in India, complementary feeding practices remain inadequate and exhibit substantial geographic variation. Although previous studies have identified several determinants of MAD, evidence on district-level spatial heterogeneity remains limited. This study examined the spatial distribution and determinants of MAD among children aged 6–23 months across India.

Methods

This study used data from the fifth round of National Family Health Survey (NFHS-5, 2019–21), including 67,507 children aged 6–23 months. District-level estimates of MAD and selected child, household, and environmental characteristics were generated for spatial analysis. Global Moran's I and Local Indicators of Spatial Association (LISA) were used to assess spatial clustering. Associations between district-level determinants and MAD were examined using ordinary least squares and spatial regression models. Multiscale geographically weighted regression (MGWR) and generalized additive models with geographically varying smooth effects were subsequently applied to investigate spatial heterogeneity and nonlinear geographic variation.

Results

Overall, 10.2% of children aged 6–23 months met the criteria for a minimum acceptable diet. Significant positive spatial clustering of MAD was observed across Indian districts (Moran's I = 0.459, $p < 0.001$). Higher district-level prevalence of breastfeeding, urban residence, greater vegetation cover (NDVI), and higher precipitation were positively associated with MAD, whereas a higher proportion of male children showed a negative association. Spatial regression models provided a better fit than conventional regression, indicating the presence of significant spatial dependence. Among all competing models, MGWR demonstrated the best model performance (AIC = − 1088.45; $R^2 = 0.613$), highlighting that the influence of key determinants varies across geographic regions. The generalized additive model further confirmed significant spatially varying effects for breastfeeding, urban residence, and NDVI.

Conclusions

Minimum acceptable diet among young children in India demonstrates marked geographic disparities that are influenced by behavioural, environmental, and contextual factors. The spatial variation in these relationships suggests that uniform national strategies may not adequately address regional nutritional inequalities. District-specific interventions that strengthen breastfeeding promotion, improve access to diverse foods, and

account for local environmental and socioeconomic conditions may enhance complementary feeding practices and contribute to improved child nutrition outcomes.

1. Introduction

Optimal infant and young child feeding (IYCF) practices during the first two years of life are fundamental to child survival, physical growth, and cognitive development [1], [2]. This period represents a critical nutritional window during which inadequate feeding can lead to long-term deficits in health and human capital formation [3]. Within this context, the Minimum Acceptable Diet (MAD) has been widely used as a composite indicator to assess complementary feeding practices among children aged 6–23 months [4]. MAD combines two essential components: Minimum Dietary Diversity (MDD), which reflects the consumption of nutritionally diverse food groups, and Minimum Meal Frequency (MMF), which captures the adequacy of feeding frequency based on a child's age and breastfeeding status [5] [6]. A substantial body of evidence has established that inadequate MAD is closely associated with adverse nutritional and developmental outcomes. Children who fail to receive adequate dietary diversity and feeding frequency are at greater risk of stunting, wasting, micronutrient deficiencies, and delayed cognitive development [7]. Empirical studies from both South Asia and sub-Saharan Africa consistently demonstrate that inadequate complementary feeding contributes significantly to anthropometric failure and poor child health outcomes. For instance, Dey et al. 2024 document a strong association between inadequate dietary intake and undernutrition in eastern India, while Kitaw et al. 2024 show that MAD exhibits pronounced geographic clustering linked to socioeconomic disadvantage and limited access to health services in Ethiopia [1], [2]. These findings indicate that complementary feeding practices are shaped not only by individual or household characteristics but also by broader structural and spatial contexts.

In India, suboptimal complementary feeding practices remain a persistent public health concern. Evidence from the National Family Health Survey (NFHS-5, 2019-21) shows that only about one in ten children aged 6–23 months receive a MAD [8]. This low prevalence reflects widespread deficiencies in both dietary diversity and meal frequency, contributing to the country's high burden of child undernutrition [2]. Despite improvements in maternal and child health service utilization, including increased institutional deliveries and antenatal care coverage, progress in complementary feeding practices has been uneven across regions. This suggests that disparities in food access, maternal knowledge, and health system reach continue to shape feeding behaviours. Previous research has identified a range of factors associated with MAD, spanning child, maternal, and household characteristics [9], [10]. Maternal education consistently emerges as a key determinant, as it enhances health awareness and feeding practices. Studies such as Acharya et al. and Pradhan et al. demonstrate that higher levels of maternal education significantly increase the likelihood of children receiving an adequate diet [5], [10]. Household economic status also plays a critical role by influencing access to diverse and nutritious foods. In addition, interaction with health services, such as antenatal care, institutional delivery, and exposure to nutrition counselling, has been shown to improve feeding practices by facilitating behavioural change [11] [12] [13]. However, these relationships are often complex and may not follow simple linear patterns. For example, the influence of maternal age, child age, or household wealth may vary across different stages or thresholds, suggesting nonlinear effects [14], [15].

Despite these insights, much of the existing literature relies on conventional parametric approaches that impose assumptions of linearity and spatial uniformity. Such models estimate average relationships and may overlook important variations in how determinants operate across different contexts. In reality, feeding practices are shaped by a combination of behavioural, socioeconomic, and programmatic factors that interact in complex ways and vary across geographic settings. Ignoring these dimensions can limit the ability to accurately identify vulnerable populations and design effective interventions. Recent studies have highlighted the importance of incorporating more flexible analytical approaches that can capture both non-linear relationships and geographic variation. Evidence suggests that complementary feeding indicators, including MAD, exhibit significant spatial clustering, reflecting shared contextual influences such as cultural practices, food environments, and access to health services. For example, Pradhan and colleagues document substantial regional disparities in dietary diversity across India, underscoring the need to account for spatial heterogeneity in nutritional research [12].

However, empirical work that simultaneously accounts for both non-linearity and spatial heterogeneity in the determinants of MAD remains limited in the Indian context [16], [17]. Most studies address these dimensions separately, thereby providing only partial insights into the complexity of complementary feeding practices. A more integrated analytical approach is needed to better understand how MAD determinants vary across populations and regions. Against this backdrop, this study examines the prevalence and determinants of MAD among children aged 6–23 months in India, while accounting for potential non-linear relationships and spatial heterogeneity in the underlying factors. By providing a more nuanced understanding of how these determinants vary across geographic contexts, the study seeks to generate evidence to inform targeted, context-specific nutrition interventions [31].

2. Data and Methods

2.1. Data Source

This study uses data from the National Family Health Survey (NFHS-5) 2019-21, a nationally representative household survey conducted by the International Institute for Population Sciences (IIPS) under the Ministry of Health and Family Welfare (MoHFW), Government of India with technical support from ICF International. The survey provides comprehensive information on population health, nutrition, and maternal and child health indicators across India. NFHS-5 collected data from 636,699 households, 724,115 women aged 15–49 years, and 101,839 children under five years of age. A two-stage sample design was used to choose the rural sample, with villages serving as the Primary Sampling Units (PSUs) at the first stage (picked with probability proportionate to size) and 22 homes chosen at random from each PSU at the second stage. A two-stage sample design was also used in urban areas, with Census Enumeration Blocks (CEB) chosen in the first stage and 22 randomly selected homes in each CEB in the second. Following a thorough mapping and household listing process in the chosen first-stage units, households were chosen for the second stage in both urban and rural locations. The present analysis included the youngest children aged 6–23 months living with their mothers in India (n = 67,507), the target population for assessing Minimum Acceptable Diet (MAD) according to WHO infant and young child feeding guidelines.

2.2. Methods

2.2.1. Variable Description

Outcome variable

Minimum Dietary Diversity (MDD) and Minimum Meal Frequency (MMF) were combined to create MAD, a composite measure that represents the amount and quality of food consumed by young children. The percentage of children between the ages of 6 and 23 months who consume items from at least five of the eight recommended food groups in the preceding 24 hours is known as Minimum Dietary Diversity, or MDD [8]These eight food groups are as follows: (1) breast milk; (2) grains, roots, and tubers; (3) legumes and nuts; (4) dairy products like milk, yogurt, and cheese; (5) meat, fish, poultry, and organ meats; (6) eggs; (7) fruits and vegetables high in vitamin A; and (8) other fruits and vegetables [2]. MMF refers to the minimum number of times a child should receive solid, semi-solid, or soft foods according to age and breastfeeding status. Breastfed infants aged 6–8 months should receive food at least twice per day, while breastfed children aged 9–23 months should receive food at least three times per day. Non-breastfed children aged 6–23 months should receive food or milk feeds at least four times per day. For non-breastfed children, age 6–23 months aged receiving solid, semisolid, or soft food or milk feeds at least four times a day. The proportion of children aged 6–23 months who had at least MMF and a MMF during the previous day were considered to have the MAD [12]. The MAD was calculated through a dietary assessment method wherein the child's mother was asked to recall all the food intake of the youngest child living with her the previous day and night. The 24-hour food recall was gathered through face-to-face interviews during household visits for the survey.

Predictor Variables

Based on existing literature on IYCF practices, several child, household, and environmental characteristics were considered as predictors of MAD among children aged 6–23 months. Previous studies suggest that complementary feeding practices are influenced not only by demographic and socioeconomic conditions but also by ecological and geographic environments that shape food availability and dietary diversity.

Accordingly, the explanatory variables included child-level characteristics such as sex of the child (male child) and age group (12–17 months), given evidence that feeding practices and nutritional needs vary by age and sex. Household and socioeconomic characteristics included maternal education (no education), household poverty status (poor household), social group composition (scheduled caste), and urban residence, which are known to influence access to nutritious foods, health information, and healthcare services. Behavioural factors included breastfeeding practices, as breastfeeding remains a critical component of complementary feeding and child nutritional adequacy.

In addition to socioeconomic determinants, environmental variables were incorporated to capture the role of agro-ecological conditions in shaping dietary practices. The Normalized Difference Vegetation Index (NDVI) was included as a proxy for vegetation cover and ecological productivity, reflecting the potential availability of food resources and agricultural conditions within districts. Higher NDVI values indicate greater vegetation density and may be associated with improved food access and dietary diversity. Precipitation was also included to account for climatic variability influencing agricultural production, food security, and seasonal food availability. Districts with more favourable rainfall conditions may exhibit better child dietary outcomes through enhanced agricultural productivity and food accessibility.

All explanatory variables were aggregated at the district level to correspond with the spatial scale of analysis and were standardized prior to modelling to facilitate comparability across predictors.

2.2.2. Geostatistical and Spatial Analysis

To examine the determinants of MAD and account for potential spatial dependence and geographic heterogeneity, a combination of global, spatial econometric, and flexible spatial modelling approaches was employed. Since complementary feeding practices are likely to vary across geographic settings due to differences in environmental, socioeconomic, and healthcare contexts, relying solely on conventional regression models may obscure important spatial processes.

Initially, an ordinary least squares (OLS) regression model was estimated to assess the overall district-level associations between MAD and selected explanatory variables. The OLS model provides global parameter estimates assuming that relationships between predictors and the outcome remain constant across geographic locations. Prior to model estimation, multicollinearity among predictors was assessed using the variance inflation factor (VIF), and diagnostic tests including the Jarque–Bera test and Breusch–Pagan test were conducted to assess residual normality and heteroskedasticity, respectively.

To evaluate whether MAD exhibited geographic clustering, exploratory spatial data analysis was performed using Global Moran's I statistic. Moran's I was calculated to assess spatial autocorrelation in district-level MAD prevalence, indicating whether neighbouring districts tended to display similar levels of dietary adequacy. Additionally, Local Indicators of Spatial Association (LISA) cluster maps were generated to identify geographic concentrations of high and low MAD prevalence across districts.

Given evidence of spatial dependence, spatial regression models were subsequently estimated to account for autocorrelation in the outcome. A Spatial Lag Model (SLM) was used to examine whether MAD in a given district was influenced by neighbouring districts, thereby capturing potential spillover effects. In parallel, a Spatial Error Model (SEM) was estimated to account for spatial dependence arising from omitted or unobserved geographically correlated factors. Model performance was assessed using Akaike Information Criterion (AIC) and explained variance (R^2), with lower AIC values indicating improved model fit.

To capture spatial heterogeneity in relationships, Geographically Weighted Regression (GWR) and Multiscale Geographically Weighted Regression (MGWR) models were estimated. Unlike OLS, which assumes geographically stationary relationships, GWR estimates local coefficients that vary across space. MGWR extends this approach by allowing each explanatory variable to operate at a distinct spatial scale through variable-specific bandwidths, thereby improving flexibility and model accuracy. An adaptive Gaussian kernel was applied to estimate local relationships, and optimal bandwidths were selected using corrected Akaike Information Criterion (AICc).

Recognizing recent methodological concerns regarding the overinterpretation of GWR-based methods, a Generalized Additive Model (GAM) with geographically varying smooth effects (GGP-GAM) was estimated as a complementary and more statistically robust framework for inference [18]. The GAM approach allows relationships between predictors and MAD to vary smoothly across geographic space while relaxing assumptions of linearity and spatial stationarity. Specifically, spatially varying coefficient smooths were estimated using Gaussian process ("gp") smoothers for longitude and latitude, allowing the influence of key

predictors to differ geographically. This framework enables the identification of nonlinear and geographically varying associations without imposing fixed spatial boundaries or uniform effects.

The GAM model can be expressed as:

$$MAD_i = \beta_0 + \sum_{k=1}^{n} f_k(lon_i, lat_i) X_{ki} + s(lon_i, lat_i) + \epsilon_i$$

Where MAD_irepresents the prevalence of MAD in district *i*, $X_k$denotes the explanatory variables, $f_k(lon_i, lat_i)$represents spatially varying smooth functions for each predictor, $s(lon_i, lat_i)$captures the baseline spatial effect, and $\epsilon_i$denotes the random error term.

The complexity and statistical significance of spatially varying relationships were evaluated using effective degrees of freedom (EDF), F-statistics, and associated significance levels. Higher EDF values indicate greater nonlinear spatial complexity in predictor effects. To assess potential overfitting and redundancy among smooth terms, concurvity diagnostics were also examined.

For all spatial analyses, MAD prevalence and explanatory variables were aggregated at the district level. Prior to model estimation, continuous variables were standardized (z-scores) to ensure comparability across predictors and facilitate interpretation of coefficients. Statistical analysis and data management were conducted using Stata (version 17), whereas spatial regression modelling, GAM estimation, and geographic visualization were performed in R software and ArcGIS Pro.

3. Results

3.1. Spatial distribution of minimum acceptable diet (MAD)

The choropleth map of district-level MAD prevalence shown in Fig. 1 revealed substantial geographic heterogeneity across India, indicating marked regional disparities in child dietary adequacy. Districts with relatively higher prevalence of MAD were predominantly concentrated in parts of southern, eastern and northeastern India, whereas lower prevalence was observed across several districts in central, northern, and western regions.

3.2. Global and spatial regression estimates

Table 1 presents the comparative findings from the ordinary least squares (OLS), spatial lag model (SLM), and spatial error model (SEM) examining district-level determinants of MAD. The OLS model explained approximately 30.7% of district-level variation in MAD (R^2 = 0.307), indicating moderate explanatory power. Across all models, breastfeeding emerged as the strongest and most consistent predictor of dietary adequacy. Districts with higher prevalence of breastfeeding demonstrated significantly better MAD outcomes in the OLS (β = 0.212*), SLM (β = 0.129*), and SEM (β = 0.123*), underscoring the importance of infant feeding practices in improving dietary adequacy. Environmental conditions also exhibited consistent associations with MAD. Higher vegetation coverage, measured using the normalized difference vegetation index (NDVI),

was positively associated with MAD in all models (OLS: β = 0.030*; SLM: β = 0.023*; SEM: β = 0.038*). Similarly, precipitation demonstrated a positive association with MAD, although the magnitude of association varied across models and was comparatively weaker in the spatial lag framework. Urban residence was positively associated with dietary adequacy (OLS: β = 0.077; *SLM: β = 0.053; SEM: β = 0.069***), suggesting that districts with higher urbanization benefit from improved food access, healthcare infrastructure, and service availability. In contrast, the proportion of male children was negatively associated with MAD across all specifications, with significant associations observed in OLS (β = −0.087), SLM (β = −0.078), and SEM (β = −0.061*).The proportion of children aged 12–17 months showed a marginally positive association with MAD in global and spatial lag models (β = 0.066† and β = 0.055†, respectively), reflecting age-related transitions in complementary feeding. However, variables such as maternal education, household poverty, caste composition, and irrigation did not demonstrate statistically meaningful associations after adjustment for spatial dependence. The significant spatial parameters in both models (ρ = 0.457* for SLM and λ = 0.500* for SEM) confirm the presence of strong spatial dependence, suggesting that dietary adequacy in one district is influenced by conditions in neighbouring districts and by spatially correlated unobserved contextual factors.

Table 1
Comparative Regression Results of OLS, Spatial Lag Model (SLM), and Spatial Error Model (SEM) for District-Level Determinants of Minimum Acceptable Diet (MAD)

Variables	**OLS**	**SLM**	**SEM**
Intercept	0.114**	0.066†	0.162***
Male child	-0.087**	-0.078**	-0.061*
Age 12–17 months	0.066†	0.055†	0.042
No education	-0.002	0.009	0.002
Breastfeeding	0.212***	0.129***	0.123***
Poor household	-0.001	-0.007	-0.010
Scheduled caste	-0.045	-0.040	-0.056
Urban residence	0.077**	0.053*	0.069*
NDVI	0.030***	0.023***	0.038***
Irrigation	-0.001	0.001	-0.005
Precipitation	0.029***	0.016*	0.026**
Spatial parameter	—	ρ = 0.457***	λ = 0.500***
Notes: **p < 0.001, *p < 0.01, p < 0.05, †p < 0.10.			
ρ = spatial autoregressive parameter in SLM; λ = spatial error parameter in SEM.			

3.3. Diagnostic assessment of OLS assumptions

Diagnostic tests confirmed important violations of OLS assumptions and justified the use of spatial modelling approaches (Table 2). The Breusch–Pagan test (90.655*) indicated significant heteroskedasticity, suggesting

non-constant variance in residuals. Likewise, the Jarque–Bera statistic (163.350*) indicated departures from normality in the residuals.

Most importantly, residual spatial dependence remained substantial after OLS estimation. The residual Moran's I statistic (I = 0.251*) indicated significant spatial autocorrelation in unexplained variation, implying that geographically proximate districts shared similar residual patterns. Collectively, these findings demonstrate that conventional regression assumptions were violated and support the application of spatially explicit modeling frameworks.

Table 2
Diagnostic Tests for the Ordinary Least Squares (OLS) Model Assessing Minimum Acceptable Diet (MAD)

Diagnostic Test	Values	Interpretation
Breusch–Pagan Test	90.655***	Heteroskedasticity present
Jarque–Bera Test	163.350***	Residuals not normally distributed
Residual Moran's I	0.251***	Spatial autocorrelation present
Global Moran's I	0.459***	Strong positive spatial clustering

3.4. Spatial heterogeneity in determinants: GWR and MGWR findings

To account for geographic non-stationarity in relationships between predictors and MAD, geographically weighted regression (GWR) and multiscale geographically weighted regression (MGWR) models were estimated. Both approaches substantially improved model fit compared with global regression models. The GWR model improved explanatory power to $R^2 = 0.585$, demonstrating that associations between MAD and its determinants vary geographically. However, the MGWR model achieved superior performance with the lowest AIC (− 1088.445) and highest explanatory power ($R^2 = 0.613$) among all competing models (Table 4), indicating that determinants operate at distinct spatial scales rather than uniformly across India. The MGWR coefficient maps further highlighted pronounced geographic variation in the effects of the predictors(see Fig. 2). Spatial variation in the effect of precipitation suggested stronger positive associations in specific agro-ecological regions, reflecting differences in agricultural productivity and food availability. Similarly, NDVI displayed marked regional heterogeneity, with greener districts generally demonstrating stronger positive effects on MAD, indicating the importance of ecological conditions for dietary adequacy. The coefficient map for male children revealed notable geographic variation in the negative association with MAD, suggesting that gender-related disparities in feeding practices may be context-specific rather than nationally uniform. Likewise, the spatial distribution of the intercept term indicated considerable residual contextual variation, suggesting the influence of unmeasured district-level factors such as food environments, policy implementation, and sociocultural norms.

3.5. GAM-based spatially varying effects and robustness assessment

To assess the robustness of the MGWR findings, a generalized additive model (GAM) with spatially varying coefficients was estimated (Table 5). The GAM explained 53.5% of deviance and demonstrated relatively strong explanatory power (adjusted $R^2 = 0.494$), confirming the presence of substantial spatial heterogeneity in MAD determinants. The GAM results revealed statistically significant spatial variation for a subset of predictors. In particular, breastfeeding (EDF = 8.794, F = 5.059*) and NDVI (EDF = 13.414, F = 3.902*) exhibited pronounced spatially varying effects, indicating that their influence on MAD differed considerably across districts. Urban residence *(EDF = 3.000, F = 3.751)** also demonstrated significant geographic variation. In contrast, age 12–17 months, poor household status, and precipitation displayed marginally significant spatial heterogeneity (†), whereas maternal education and scheduled caste composition showed no statistically significant spatial variation. The significant baseline spatial smoother (EDF = 9.510, F = 2.018*) further suggested the persistence of underlying geographic structure beyond measured covariates. The GAM-GGP maps shown in Fig. 3 reinforced these findings by illustrating substantial geographic variation in the strength and direction of predictor effects. Spatial patterns were especially pronounced for precipitation and NDVI, indicating that environmental influences on child dietary adequacy vary considerably across India's ecological zones.

Table 4
Model Comparison of Global and Spatial Regression Models

Model	AIC	R^2
OLS	-924.182	0.307
SLM	-1027.779	0.430
SEM	-1020.999	0.431
GWR	-1025.029	0.585
MGWR	**-1088.445**	**0.613**
Notes: Lower AIC values indicate better model fit.		

3.6. Comparative model performance

A comparative assessment of model performance demonstrated clear improvements when spatial dependence and heterogeneity were incorporated (Table 4). The OLS model exhibited the weakest fit (AIC = −924.182; $R^2 = 0.307$), whereas spatial econometric models substantially improved explanatory power (SLM: $R^2 = 0.430$; SEM: $R^2 = 0.431$).

Flexible spatial models further enhanced model performance. The GAM accounted for a considerable proportion of variation ($R^2 = 0.494$), while the GWR model substantially improved explanatory power ($R^2 = 0.585$). However, the MGWR model emerged as the best-fitting specification, with the lowest AIC (− 1088.445) and highest R^2 (0.613), indicating that multiscale spatial processes provide the most accurate representation of district-level variation in MAD across India.

Table 5
Generalized Additive Model (GAM) Results Showing Spatially Varying Effects on Minimum Acceptable Diet (MAD)

Smooth Terms	EDF	F-value
Age 12–17 months†	3.000	2.401
No education	3.000	0.345
Breastfeeding***	8.794	5.059
Poor household†	6.777	1.830
Scheduled caste	3.000	1.768
Urban residence*	3.000	3.751
NDVI***	13.414	3.902
Precipitation†	7.222	1.717
Spatial smoother (*s*(lon, lat))*	9.510	2.018

Notes: ***$p < 0.001$, **$p < 0.01$, p *< 0.05, †$p < 0.10$. EDF = effective degrees of freedom. Higher EDF values indicate greater spatial complexity or nonlinearity in the association.

4. Discussion

This study examined district-level determinants of MAD among children in India using a progression of global, spatial, and multiscale models. The findings demonstrate that child dietary adequacy is not only socially and environmentally determined but also strongly shaped by spatial processes, including both spatial dependence and spatial heterogeneity.

The study found that across model specifications, behavioural and environmental factors emerge as the most consistent and influential determinants of MAD. In particular, early initiation of breastfeeding shows a robust positive association with dietary adequacy and exhibits pronounced spatial variation. This underscores the central role of maternal caregiving practices in shaping child nutrition outcomes, while also indicating that the effectiveness of such practices varies across regional contexts [20] [21]. Environmental conditions, proxied by vegetation (NDVI) and precipitation, also display strong and spatially heterogeneous associations with MAD. These findings highlight the importance of ecological context in influencing food availability and dietary diversity. Regions with more favourable agro-ecological conditions appear to provide a supportive environment for achieving adequate child nutrition, although the strength of this relationship varies geographically [22]. Urbanization is another significant determinant, suggesting that access to markets, services, and infrastructure plays an important role in improving dietary outcomes. However, the spatial variation observed in its effects indicates that the advantages of urban residence are not uniformly distributed, reflecting disparities in urban infrastructure and service delivery [12] [23]. In contrast, traditional socioeconomic indicators such as poverty, caste, and maternal education do not exhibit strong or consistent effects in the fully adjusted models, nor do they show significant spatial variation in the GAM-SVC framework, which conforms to several past studies [18] [7], [21], [24]. This does not imply that these factors are

unimportant; rather, their influence may be mediated through more proximate behavioural and environmental pathways or may operate at broader structural levels that are less spatially differentiated at the district scale.

The presence of significant spatial autocorrelation in OLS residuals confirms that child nutrition outcomes are geographically clustered. Spatial regression models (SLM and SEM) improve model fit substantially, indicating that neighbouring districts exhibit similar patterns of dietary adequacy due to shared socio-cultural, economic, and environmental contexts [25] [26]. These findings suggest the existence of spatial spillover effects, where practices, infrastructure, and food systems extend beyond administrative boundaries. They also point to the role of unobserved regional factors such as policy implementation, agricultural systems, and cultural norms that influence child nutrition in spatially contiguous areas [12].

The MGWR results reveal that relationships between determinants and MAD vary across space and operate at different geographic scales. This underscores the limitation of global models, which assume uniform effects, and highlights the importance of accounting for spatial non-stationarity [27]. The superior performance of MGWR indicates that child nutrition is governed by multiscale processes. Behavioural factors such as breastfeeding tend to exhibit localized effects, reflecting community-level practices and norms. In contrast, environmental variables such as vegetation and precipitation operate over broader spatial scales, consistent with regional agro-ecological patterns. Structural factors like urbanization may span intermediate scales, reflecting both local infrastructure and broader development gradients [28]. This multiscale perspective provides a more nuanced understanding of geographic inequalities in child nutrition and suggests that interventions must be tailored to the spatial scale at which determinants operate.[27]

The GAM-based spatially varying coefficient model provides an important robustness check for the MGWR findings. While MGWR suggests widespread spatial variation across multiple predictors, the GAM-SVC results indicate that spatial heterogeneity is concentrated in a subset of variables—specifically breastfeeding, NDVI, and urbanization[29]. This distinction is methodologically important. MGWR, as an exploratory tool, is effective in identifying potential spatial variation and scale differences. However, the GAM framework, grounded in a likelihood-based approach, offers more conservative and statistically robust inference. The convergence of results across these models, particularly for key behavioural and environmental variables, strengthens confidence in the substantive findings [30]. At the same time, the GAM results suggest that not all determinants vary spatially, emphasizing the need to distinguish between truly spatially varying processes and those that are relatively stable across regions. This combined approach addresses recent critiques of GWR-based methods and demonstrates the value of integrating complementary modeling frameworks [18], [31].

The findings have important implications for policy and program design. The strong and spatially varying influence of breastfeeding practices suggests that interventions promoting optimal infant feeding should be tailored to local contexts, taking into account regional cultural norms and health system capacity. The role of environmental conditions highlights the need to integrate nutrition policy with agricultural and climate-sensitive interventions. Enhancing food availability and diversity in ecologically constrained regions may require targeted investments in irrigation, crop diversification, and climate-resilient agriculture. The spatial variation in urban effects indicates that improving urban nutrition outcomes requires attention to intra-urban inequalities, including access to affordable and diverse foods, healthcare, and social services. More broadly,

the evidence of spatial clustering and multiscale heterogeneity suggests that uniform, nationwide interventions may be insufficient. Instead, geographically targeted strategies that account for regional variation and spatial interdependencies are likely to be more effective.

Several limitations of this study should be acknowledged. First, the analysis is based on cross-sectional data, which limits causal inference. Second, district-level aggregation may mask intra-district variation and individual-level dynamics. Third, while MGWR and GAM-SVC capture spatial heterogeneity, they do not fully account for all sources of spatial dependence or potential endogeneity. Future research could extend this work by incorporating longitudinal data, exploring causal pathways, and integrating additional contextual variables such as food markets, health service availability, and policy implementation. In the meantime, integrating multiscale and statistically grounded spatial models, this study provides new insights into the geographic structure of nutritional inequalities.

5. Conclusion

This study examined the district-level determinants and spatial heterogeneity of minimum acceptable diet (MAD) among children aged 6–23 months in India using global, spatial econometric, and geographically varying models. The findings reveal substantial geographic disparities and significant spatial clustering in MAD, indicating that child dietary adequacy is shaped by behavioural, environmental, and spatial factors. Breastfeeding, urban residence, NDVI, and precipitation emerged as important positive determinants of MAD, whereas the proportion of male children showed a negative association. Spatial models further demonstrated that these relationships vary geographically, with MGWR and GGP-GAM highlighting significant spatial heterogeneity, particularly for breastfeeding, NDVI, and urban residence.

The findings underscore that uniform nutrition interventions may be insufficient to address regional disparities in child feeding practices. Instead, geographically targeted strategies that strengthen breastfeeding promotion, improve food access and diversity, and account for local ecological and infrastructural conditions are needed to improve child dietary adequacy across India.

Declarations

Ethical approval:

The study is based on nationwide secondary data sets from the NFHS-5 (2019-21) survey. As part of the original surveys, consent was obtained from participants, and data is publicly available with no identifiable information on the survey participants. This dataset is available in the public domain; therefore, no ethical approval was required for the present study.

Consent to participate: Not applicable.

Consent to publish: Not applicable.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest: The authors declare no competing interests.

Clinical trial number: Not applicable.

Author Contributions Statement: MRP supervised the study. MRP and RB developed the concept for this study and wrote the methods section. SND performed data analysis. SND and RB wrote the background, interpretation text, and discussion. RB and MRP performed editorial checks and reviewed the manuscript for intellectual content. SND performed in corresponding with the journal. All authors read and approved the final version of the manuscript.

Availability of data and materials

The datasets generated and/or analyzed during this study are available on the DHS website at [DHS Program Datasets](https://dhsprogram.com/data/available-datasets.cfm). The shapefile utilized in this study to prepare maps can be easily accessed through the Spatial Data Repository, The Demographic and Health Surveys Program website (https://spatialdata.dhsprogram.com/boundaries/#view=map&countryId=IA&surveyId=541&level=1%2C%202).

References

1. Kitaw TA, Abate BB, Derese Tilahun B, Haile RN. Geospatial pattern of level of minimum acceptable diet and its determinants among children aged 6–23 months in Ethiopia. Spatial and multiscale geographically weighted regression analysis. Front Public Health. Jun. 2024;12:1348755. 10.3389/fpubh.2024.1348755.
2. Dey D, Ghosh R, Das DK, Das M. Minimum Acceptable Diet, Anthropometric Failure and Correlates among Children Aged 6–23 Months in a Rural Area of Murshidabad, West Bengal, *Natl. J. Community Med.*, vol. 15, no. 06, pp. 468–473, Jun. 2024, 10.55489/njcm.150620243832
3. Dejene Y, Mezgebu GS, Tadesse SE. Minimum acceptable diet and its associated factors among children aged 6–23 months in Lalibela, northeast Ethiopia: a community-based cross-sectional study. J Nutr Sci. 2023;12:e41. 10.1017/jns.2023.24.
4. World Health Organization. Indicators for assessing infant and young child feeding practices: part 2: measurement. World Health Organization, 2010. Accessed: Mar. 07, 2026. [Online]. Available: https://iris.who.int/bitstream/handle/10665/44306/9789241599290_eng.pdf
5. Infant and young child feeding. Accessed: Apr. 07. 2026. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/infant-and-young-child-feeding
6. Acharya A, Pradhan MR, Das AK. Determinants of minimum acceptable diet feeding among children aged 6–23 months in Odisha, India. Public Health Nutr, 24, 12, pp. 3834–44, 10.1017/S1368980021002172
7. Custodio E, Herrador Z, Nkunzimana T, Węziak-Białowolska D, Perez-Hoyos A, Kayitakire F. Children's dietary diversity and related factors in Rwanda and Burundi: A multilevel analysis using 2010 Demographic and Health Surveys. PLoS ONE. Oct. 2019;14(10):e0223237. 10.1371/journal.pone.0223237.
8. NFHS. Accessed: Mar. 12, 2026. [Online]. Available: https://www.nfhsiips.in/nfhsuser/nfhs5.php

9. Batal M, Boulghourjian C, Akik C. Complementary feeding patterns in a developing country: a cross-sectional study across Lebanon, *East. Mediterr. Health J.*, vol. 16, no. 02, pp. 180–186, Feb. 2010, 10.26719/2010.16.2.180
10. Harindintwari I, Mochama M, Nsanzabera C, Kubahoniyesu T. Factors Associated With Minimum Acceptable Diet among Children Aged 6 to 23 Months in Rwanda, *Rwanda J. Med. Health Sci.*, vol. 7, no. 3, pp. 445–453, Nov. 2024, 10.4314/rjmhs.v7i3.6
11. Kambale RM, et al. Minimum acceptable diet among children aged 6–23 months in South Kivu, Democratic Republic of Congo: a community-based cross-sectional study. BMC Pediatr. May 2021;21(1):239. 10.1186/s12887-021-02713-0.
12. Pradhan MR, Saikia D, Mondal S, Mudi P. Prevalence and predictors of minimum acceptable diet (MAD) feeding among tribal children aged 6–23 months in India, *Biodemography Soc. Biol.*, vol. 69, Apr. 2024, 10.1080/19485565.2024.2344481
13. Dhami BK, Nath D, Lamichhane R. Factors influencing minimum acceptable diet (MAD) intake among children aged 6–23 months in remote mid-Himalayan region of Sudurpaschim, Nepal. BMC Public Health. Jan. 2025;25(1):237. 10.1186/s12889-025-21468-2.
14. Taren D, Chen J. A positive association between extended breast-feeding and nutritional status in rural Hubei Province, People's Republic of China. Am J Clin Nutr. 1993;58(6):862–7.
15. Mumbare SS, Rege R. Ante natal care services utilization, delivery practices and factors affecting them in tribal area of north maharashtra, *Indian J. Community Med. Off. Publ. Indian Assoc. Prev. Soc. Med.*, vol. 36, no. 4, pp. 287–290, Oct. 2011, 10.4103/0970-0218.91331
16. Saaka M, Larbi A, Mutaru S, Hoeschle-Zeledon I. Magnitude and factors associated with appropriate complementary feeding among children 6–23 months in Northern Ghana, *BMC Nutr.*, vol. 2, no. 1, p. 2, Jan. 2016, 10.1186/s40795-015-0037-3
17. Dhami MV, Ogbo FA, Osuagwu UL, Agho KE. Prevalence and factors associated with complementary feeding practices among children aged 6–23 months in India: a regional analysis. BMC Public Health. Aug. 2019;19(1):1034. 10.1186/s12889-019-7360-6.
18. Comber A, Harris P, Brunsdon C. Multiscale spatially varying coefficient modelling using a Geographical Gaussian Process GAM, *Int. J. Geogr. Inf. Sci.*, vol. 38, no. 1, pp. 27–47, Oct. 2023.
19. Acharya A, Pradhan MR, Das AK. Determinants of minimum acceptable diet feeding among children aged 6–23 months in Odisha, India, *Public Health Nutr.*, vol. 24, no. 12, pp. 3834–3844, Aug. 2021, 10.1017/S1368980021002172
20. Nguyen PH et al. Jun., Maternal nutrition practices in Uttar Pradesh, India: Role of key influential demand and supply factors, *Matern. Child. Nutr.*, vol. 15, no. 4, p. e12839, 2019, 10.1111/mcn.12839
21. Ahoya B, Kavle JA, Straubinger S, Gathi CM. Accelerating progress for complementary feeding in Kenya: Key government actions and the way forward. Matern Child Nutr. 2019;15:e12723. 10.1111/mcn.12723.
22. Medrano L, et al. Multiple Sustainable Practices Are Crucial for Enhancing the Provisioning of Agroecosystem Services Worldwide. Ecol Lett. Dec. 2025;28(12):e70276. 10.1111/ele.70276.
23. Joshi N, Agho KE, Dibley MJ, Senarath U, Tiwari K. Determinants of inappropriate complementary feeding practices in young children in Nepal: secondary data analysis of Demographic and Health Survey 2006. Matern Child Nutr. 2012;8(s1):45–59. 10.1111/j.1740-8709.2011.00384.x.

24. Dhawan D, Pinnamaneni R, Viswanath K. Association between mass media exposure and infant and young child feeding practices in India: a cross-sectional study. Sci Rep. Nov. 2023;13(1):19353. 10.1038/s41598-023-46734-4.
25. Fotheringham AS, Yang W, Kang W. Multiscale Geographically Weighted Regression (MGWR). Ann Am Assoc Geogr. Nov. 2017;107(6):1247–65. 10.1080/24694452.2017.1352480.
26. Khan J, Mohanty SK. Spatial heterogeneity and correlates of child malnutrition in districts of India. BMC Public Health. Aug. 2018;18(1):1027. 10.1186/s12889-018-5873-z.
27. Tebeje TM, et al. A multiscale geographically weighted regression analysis of teenage pregnancy and associated factors among adolescents aged 15 to 19 in Ethiopia using the 2019 mini-demographic and health survey. PLoS ONE. Sep. 2024;19(9):e0310025. 10.1371/journal.pone.0310025.
28. de Sherbinin A. The Biophysical and Geographical Correlates of Child Malnutrition in Africa. Popul Space Place. Jan. 2011;17. 10.1002/psp.599.
29. Cheng L, Yan M, Zhang W, Guan W, Zhong L, Xu J. Interpretable Digital Soil Organic Matter Mapping Based on Geographical Gaussian Process-Generalized Additive Model (GGP-GAM). Agriculture. Sep. 2024;14:1578. 10.3390/agriculture14091578.
30. Comber A et al. *Encapsulating Spatially Varying Relationships with a Generalized Additive Model*. 2024. 10.20944/preprints202411.0375.v1
31. Dwivedi SN. Understanding Sociodemographic Determinants of Voluntary Cesarean Section Deliveries in India through Geospatial Modeling using Multiscale Geographically Weighted Regression (MGWR). Discov Public Health. Nov. 2024;21(1):203. 10.1186/s12982-024-00325-4.

Figures

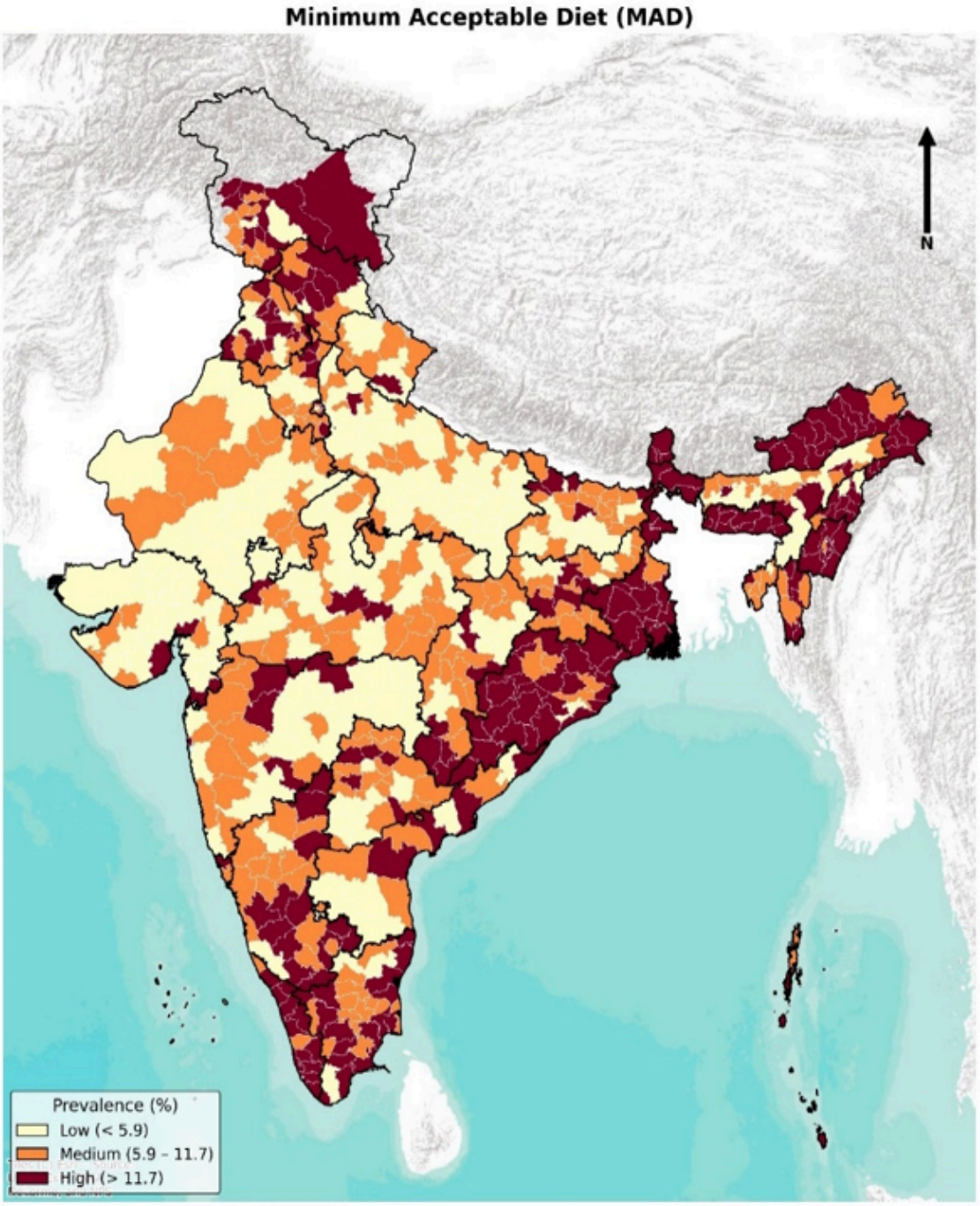


Figure 1

Spatial Distribution of Minimum Acceptable Diet (MAD) Among Children Aged 6–23 Months Across Districts in India, 2019-21

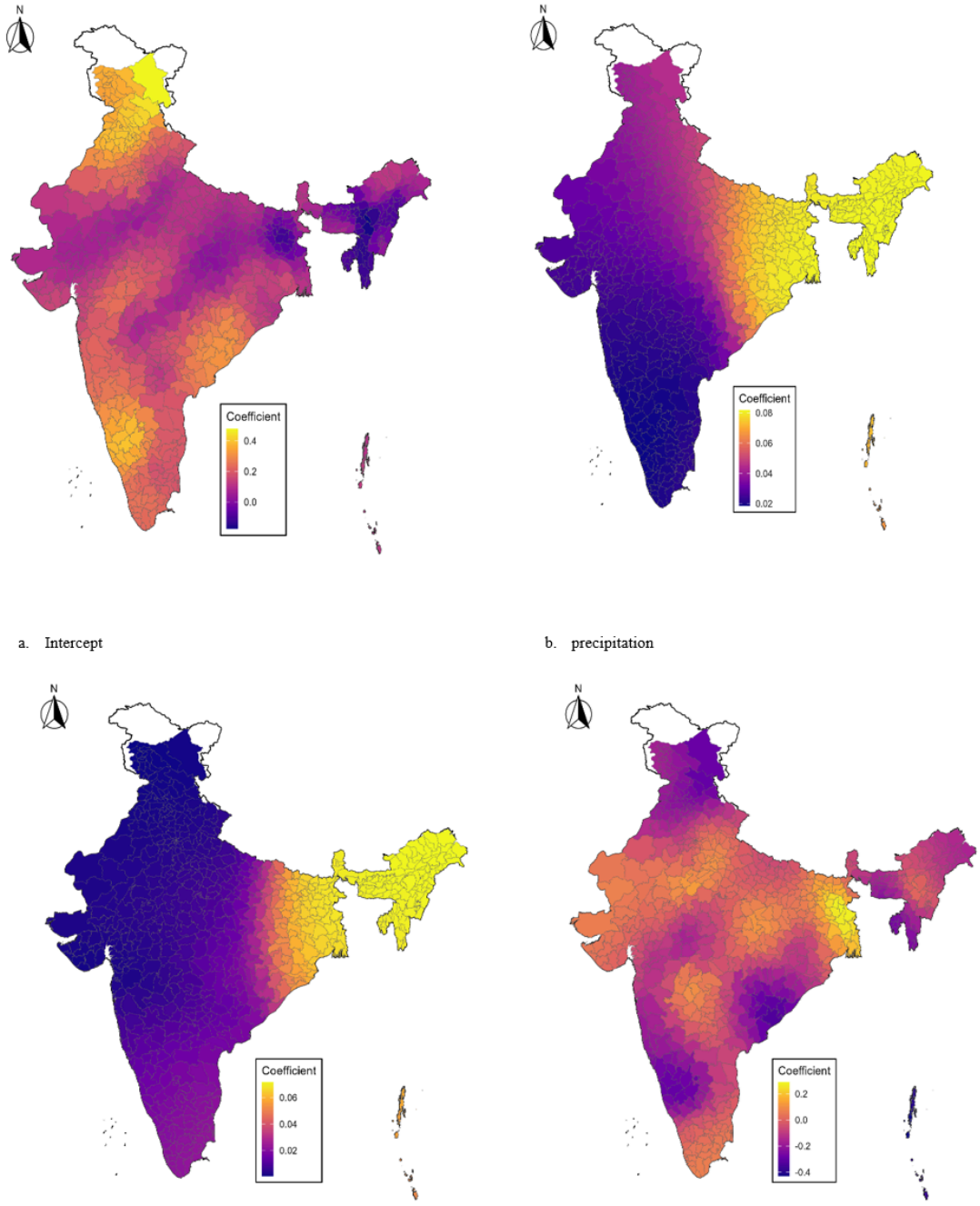
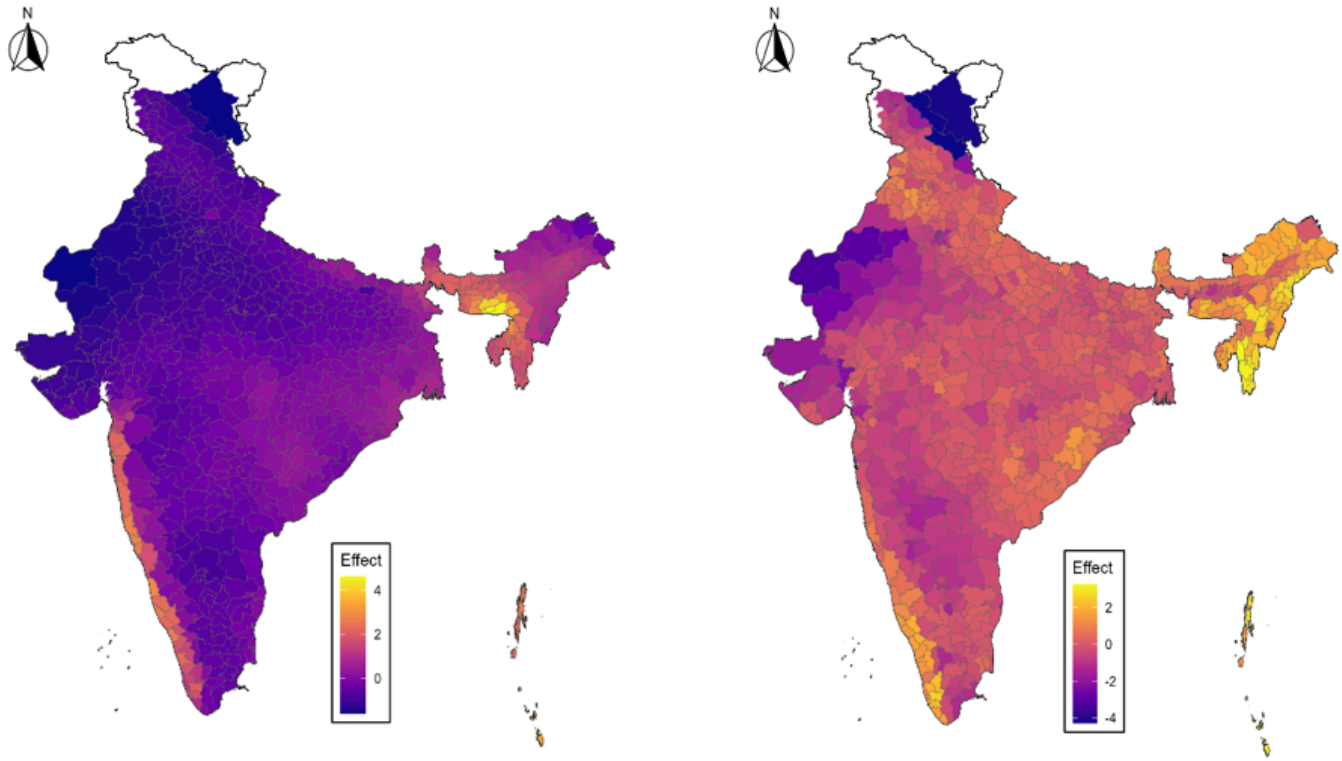


Figure 2

Spatial Variation in MGWR Coefficients for Determinants of Minimum Acceptable Diet (MAD) Across Districts in India



a. Precipitation

b. NDVI

Figure 3

Spatially Varying Effects of Determinants of Minimum Acceptable Diet (MAD) Based on GAM-GGP Maps