

Spatial analysis of stunting risk factors in Central Java, Indonesia: A geographically weighted regression approach (2023 data)

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ABSTRACT

The 2022 Indonesian Nutritional Status Survey (SSGI) reported a stunting prevalence of 20.8% in Central Java. Although various studies have examined its risk factors, few have applied a spatial perspective. This study aims to analyze regional variations in stunting risk factors and their contribution to rising stunting rates. This is a quantitative explanatory study employing the geographically weighted regression (GWR) method. Secondary data were obtained from the Central Java Health Profile and *Badan Pusat Statistik Indonesia* (BPS) in 2023, using a total sampling of 35 districts/cities. The GWR results indicated that chronic energy deficiency (CED; $\beta = 0.0014$, $p = 0.068$) and exclusive breastfeeding ($\beta = 0.0791$, $p = 0.087$) were marginally positively associated with stunting. Low birth weight (LBW) showed a significant positive association ($\beta = 0.1009$, $p = 0.041$), while access to improved sanitation had a strong negative effect ($\beta = -0.1882$, $p = 0.004$). Iron supplementation (≥ 90 tablets) was not significant ($\beta = -0.0629$, $p = 0.134$), whereas access to improved drinking water was positively and significantly correlated with stunting ($\beta = 0.3778$, $p = 0.028$). These findings contradict existing theories, particularly where higher rates of exclusive breastfeeding and access to clean water are unexpectedly associated with increased stunting in several regions. This suggests the need for further in-depth investigation in those areas to better understand the underlying factors.

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1. INTRODUCTION

Stunting remains a major global public health concern, affecting more than 22% of children under five worldwide, and resulting in long-term impairments in physical growth, cognitive development, and disease susceptibility [1]. The World Health Organization (WHO) classifies stunting prevalence above 20% as a high public health burden, underscoring the urgency of targeted interventions in affected regions. Stunting remains a major public health challenge in Indonesia, affecting one in five children under five [2]. National data showed a prevalence of 24.4% in 2021, while the 2022 Indonesian Nutritional Status Survey (SSGI) reported that Central Java had a stunting prevalence of 20.8%, still above the WHO target of <20%. Despite ongoing interventions, the Provincial Government of Central Java aims to reduce stunting to 14% by 2024 [3].

Previous studies have identified key determinants of stunting, including chronic energy deficiency, low birth weight, inadequate sanitation, limited access to health services, and suboptimal feeding practices, providing important insights into nutritional and environmental risks [4], [5]. However, most analyses rely on

global regression models that assume uniform relationships across regions, potentially overlooking substantial district-level variation. In Central Java, where geographic, socioeconomic, and environmental conditions differ widely, such uniformity is unlikely.

Recent global research suggests that risk factors for stunting vary spatially, and ignoring this heterogeneity can obscure critical local patterns and reduce the effectiveness of interventions [6], [7]. Yet, despite the growing application of spatial methods in public health, studies employing geographically weighted regression (GWR) to analyze stunting determinants remain limited, especially in the Southeast Asian context. A clear research gap exists: to date, no studies have mapped stunting risk factors in Central Java using GWR. Understanding spatial heterogeneity is crucial, as interventions that do not consider local variation risk being ineffective or misdirected.

To address this gap, this study applies GWR to analyze stunting risk factors across 35 districts in Central Java. By generating location-specific parameter estimates, GWR reveals localized patterns that are often obscured in global models. The findings are expected to strengthen spatially targeted intervention strategies and provide evidence-based guidance for policymakers in designing region-specific stunting reduction programs.

2. METHOD

This study employed an explanatory quantitative design with a spatial approach using GWR to analyze risk factors for stunting across all regencies and cities in Central Java Province. GWR was selected due to its ability to capture spatial heterogeneity, producing local parameter estimates that vary across regencies and cities, thereby allowing for a more detailed analysis of the relationships among variables. The study population included all 35 regencies and cities, with full sampling to ensure complete spatial coverage. Secondary data were obtained from the Central Java Provincial Statistics Agency and the Central Java Health Profile (2023), encompassing stunting prevalence, maternal and child health indicators, health services, and environmental conditions as shown in Figure 1.

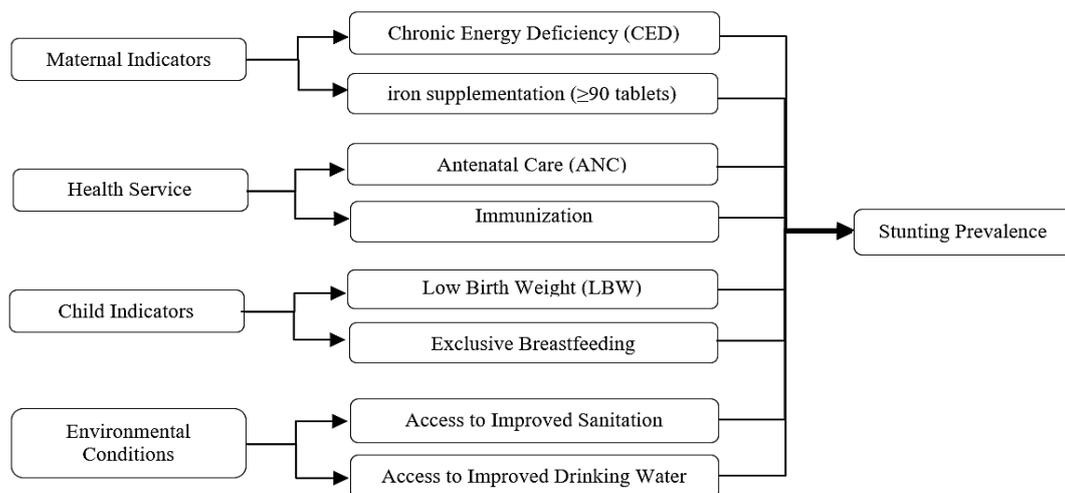


Figure 1. Research variable

This study utilized several key health indicators. Stunting was measured as the percentage of children under five with $HAZ < -2$ SD. Figure 1 shows that maternal factors included chronic energy deficiency (CED), defined as pregnant women with a $BMI < 18.5$ kg/m^2 , and iron supplementation (≥ 90 tablets), defined as consumption of iron tablets for ≥ 90 days. Health service aspects comprised the first and fourth antenatal care (ANC) visits and the coverage of complete child immunizations. Infant conditions were assessed by the percentage of low birth weight (LBW), < 2.5 kg) and exclusive breastfeeding for infants aged 0-6 months. Environmental factors were represented by access to improved sanitation and improved drinking water in accordance with national standards [5], [8], [9].

The GWR analysis was conducted through a series of systematic steps. The initial step involved data preparation, including the collection of stunting data and independent variables, as well as the cleaning of outliers and inconsistent data. Variable selection was performed using stepwise global ordinary least squares (OLS) regression, assessing changes in AIC and Adjusted R^2 ; variables that improved model fit and exhibited

potential spatial variation were retained, while irrelevant or globally homogeneous variables were excluded [10]. The next step involved the determination of kernel type and bandwidth, selecting either fixed or adaptive kernels, and identifying the optimal bandwidth through cross-validation (CV) to minimize the corrected AIC (AICc) [11]. The GWR model was then executed using the selected variables to obtain local parameter estimates (β) for each regency/city. Model evaluation was conducted by comparing local and global R^2 , inspecting residuals for potential specification errors, and performing sensitivity analyses to assess model robustness.

The final step involved the interpretation of results, including the creation of thematic maps for each variable, the analysis of spatial variations in the relationships between risk factors and stunting, and the exploration of potential confounding factors that may influence spatial patterns. All analyses were performed using RStudio, which supports statistical modeling and spatial analysis. Nevertheless, this analysis has limitations, particularly due to reliance on secondary data and its cross-sectional design, which restricts data quality control and causal inference; longitudinal studies or mixed-method approaches are recommended for future research.

3. RESULTS AND DISCUSSION

3.1. Result

3.1.1. Spatial distribution of stunting prevalence in Central Java (2023 data)

The distribution of stunting prevalence based on the collected data is presented in Figure 2. It shows that regions within Central Java Province are predominantly classified as having a high prevalence (10% -14%), with 15 districts/cities falling into this category. Spatial visualization of the distribution further indicates that areas with very high prevalence ($\geq 15\%$), such as Brebes, Tegal, Banyumas, Banjarnegara, Wonosobo, Magelang, and Magelang City, share similar environmental characteristics, namely regions abundant in water resources. However, in several remote villages, water quality remains a significant concern due to contamination and limited access to improved sanitation facilities.

This finding is consistent with previous studies, such as research conducted in Purwojati Subdistrict, Banyumas District, Central Java. The study revealed that 68.4% of households had poor sanitation, 92% demonstrated inadequate waste management, and 68.9% relied on non-plumbing water sources. There was a significant difference in the height-for-age z-scores based on latrine hygiene ($p = 0.032$), indicating that latrine cleanliness was associated with stunting prevalence [12]. Moreover, a study conducted in Brebes also found that the combination of unimproved latrines and untreated drinking water consumption increased the risk of stunting by more than threefold [13].

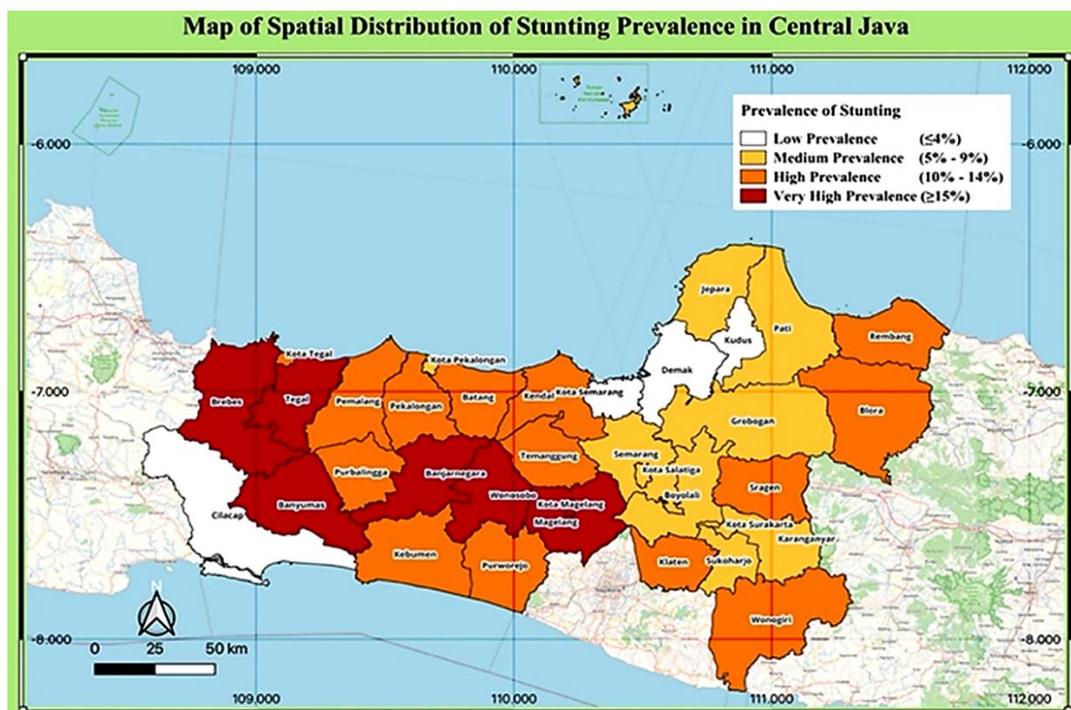


Figure 2. Spatial distribution of stunting prevalence in Central Java, 2023

3.1.2. Global regression analysis

The selection of independent variables was conducted to identify the factors that most significantly influence the spatial variation of stunting prevalence at the district and municipal levels. This process aimed to ensure that only relevant and statistically significant variables were included in the GWR model, thereby enhancing the accuracy and interpretability of the spatial analysis. The independent variables used in this study, as presented in Table 1, include maternal and child health indicators (immunization, first antenatal care, fourth antenatal care, CED, iron supplementation (≥ 90 tablets) for pregnant women, LBW infant, exclusive breastfeeding), sanitation access, and access to improved drinking water.

Based on Table 1, the stepwise OLS results, the full model initially demonstrated an AIC of 204.369 and an adjusted R^2 of 0.304, indicating moderate explanatory power at the global level. Among the individual predictors, first antenatal care (K1) showed the strongest global performance (AIC = 199.487; adjusted R^2 = 0.3587), followed by Fourth Antenatal Care (K4) (AIC = 200.816; adjusted R^2 = 0.3476) and Immunization (AIC = 202.438; adjusted R^2 = 0.3298). These variables consistently improved global model fit and exhibited relatively high adjusted R^2 values, suggesting limited spatial heterogeneity. Consequently, they were excluded from the GWR model because strong global predictors typically contribute little additional insight when modeled locally. In contrast, variables such as improved sanitation (adjusted R^2 = 0.3100), Iron supplementation (≥ 90 tablets) (adjusted R^2 = 0.3282), exclusive breastfeeding (adjusted R^2 = 0.2943), improved drinking water (adjusted R^2 = 0.2708), CED (adjusted R^2 = 0.2271), and LBW Infant (adjusted R^2 = 0.1989) demonstrated weaker global explanatory power. These predictors were therefore retained for GWR, as lower adjusted R^2 values and higher AIC scores indicate greater potential for spatial non-stationarity, aligning with recommendations by Comber *et al.* [10] that GWR is most effective for variables exhibiting spatially varying relationships [14]. Subsequently, the selected variables were analyzed using linear regression analysis of stunting prevalence, as presented in Table 2.

Based on the global regression analysis results presented in Table 2, the intercept value of -14.67 is not statistically significant. Overall, the model indicates that access to improved sanitation (β = -0.188, $p < 0.01$) is highly significant. Access to improved drinking water (β = 0.3778, $p < 0.05$) and LBW (β = 0.1009, $p < 0.05$) are also statistically significant. CED (p = 0.068) and exclusive breastfeeding (p = 0.078) demonstrate marginal significance at the 10% level. In contrast, iron supplementation (≥ 90 tablets) (p = 0.134) is not statistically significant.

Table 1. Independent variable selection of stunting risk factors in Central Java (2023 data)

Variable	AIC	SBC	SBIC	R^2	Adj. R^2
Full Model	204.369	221.478	112.724	0.48848	0.30433
Improved sanitation	202.900	218.400	110.500	0.47500	0.31000
Immunization	202.438	217.991	109.947	0.48748	0.32978
Fourth antenatal care	200.816	214.814	107.314	0.48191	0.34759
First antenatal care	199.487	211.930	104.892	0.47188	0.35871
Iron supplementation (≥ 90 tablets)	200.344	211.232	103.890	0.42696	0.32816
Exclusive breastfeeding	201.249	210.582	103.380	0.37736	0.29434
Improved drinking water	201.545	209.322	102.825	0.33515	0.27081
CED	202.692	208.914	103.273	0.27260	0.22714
LBW infant	203.025	207.691	103.371	0.22246	0.19890

Table 2. Results of linear regression analysis of stunting risk factors in Central Java (2023 data)

Variable	Coefficient (β)	SE	t-Statistic	p-value	Sig
(Intercept)	-14.67	15.18	-0.967	0.342	ns
CED	0.001446	0.000762	1.898	0.068	*
Iron supplementation (≥ 90 tablets)	-0.06288	0.04075	-1.543	0.134	ns
LBW infant	0.1009	0.04715	2.139	0.041	**
Exclusive breastfeeding	0.0791	0.04464	1.772	0.087	*
Improved sanitation	-0.1882	0.05998	-3.137	0.004	***
Improved drinking water	0.3778	0.1628	2.321	0.028	**

3.1.3. GWR analysis

Based on Table 3, the results of the GWR analysis revealed substantial spatial variation in the relationship between multiple risk factors and stunting prevalence across Central Java Province. The intercept values ranged from -17.73 to 0.068, indicating a broad variability in baseline stunting levels independent of explanatory variables, suggesting the potential influence of unobserved contextual factors. CED showed a consistently positive effect across all districts, with coefficient values narrowly ranging from 0.00117 to 0.00170. With a median coefficient of 0.001357, this implies that for every 1% increase in the prevalence of CED among mothers, stunting prevalence increases by approximately 0.0014%.

The coverage of iron supplementation (≥ 90 tablets) for pregnant women had predominantly negative coefficients, ranging from -0.098 to 0.0056, with a median of -0.028. This suggests that a 1% increase in iron supplementation (≥ 90 tablets) coverage may reduce stunting prevalence by around 0.028%. However, a few districts exhibited nearly neutral or slightly positive effects, which may reflect external unaccounted-for influences. LBW infants were also found to have a strong and consistent positive association with stunting, with coefficient values from 0.104 to 0.139 and a median of 0.118. This indicates that each 1% increase in the proportion of LBW infants is associated with an approximate 0.118% increase in stunting prevalence.

An unexpected finding emerged regarding exclusive breastfeeding, which showed a positive relationship with stunting (coefficients ranging from 0.039 to 0.089, median 0.070). This suggests that a 1% increase in exclusive breastfeeding coverage was paradoxically associated with a 0.07% increase in stunting prevalence. This contradicts existing literature and may be attributable to confounding factors such as poor maternal nutrition, inadequate complementary feeding practices post-6 months, or potential reporting inaccuracies. A similar paradox was found in the case of access to improved drinking water, where coefficients ranged from 0.184 to 0.395 (median approximately 0.301), implying that a 1% increase in access to improved water sources was linked to a 0.30% increase in stunting prevalence. This counterintuitive relationship may stem from discrepancies between administratively defined “safe” water and its actual microbiological quality, or due to overlapping socioeconomic vulnerabilities.

Conversely, improved sanitation consistently showed a protective effect, with all coefficients being negative (ranging from -0.238 to -0.174, median -0.1975). This supports the theoretical premise that access to improved sanitation reduces the risk of infectious diseases and chronic undernutrition. Specifically, a 1% increase in improved sanitation coverage was associated with a reduction in stunting prevalence of approximately 0.20%. These findings underscore the importance of spatially sensitive policymaking, as the determinants of stunting exhibit significant local variation. Hence, a uniform, one-size-fits-all policy approach is unlikely to be effective across heterogeneous regional contexts.

Table 3. The local GWR coefficient estimates of stunting risk factors in Central Java (2023 data)

Variable	Min.	1st qu.	Median	3rd qu.	Max.
(Intercept)	-17.727432	-11.435276	-7.6075826	-3.8472859	0.0677
CED	0.0011684	0.0012603	0.0013567	0.0014679	0.0017
Iron supplementation (≥ 90 tablets)	-0.0979556	-0.0762899	-0.0284569	-0.0142488	0.0056
LBW infant	0.1040499	0.113725	0.1182099	0.1242835	0.139
Exclusive breastfeeding	0.0386162	0.0548879	0.0704245	0.0788433	0.0888
Improved sanitation	-0.2379249	-0.2092793	-0.1975011	-0.1857861	-0.1744
Improved drinking water	0.1841294	0.2700569	0.3014717	0.3294641	0.3947

3.2. Discussion

Figure 3 presents the spatially varying coefficients derived from the GWR model for key determinants of stunting across districts in Central Java. The maps illustrate pronounced spatial heterogeneity in the magnitude and direction of associations between stunting prevalence and Figure 3(a) shows chronic energy deficiency among pregnant women, Figure 3(b) shows iron supplementation (≥ 90 tablets), Figure 3(c) shows low birth weight, Figure 3(d) shows exclusive breastfeeding coverage, Figure 3(e) shows access to improved sanitation, and Figure 3(f) shows access to improved drinking water. Chronic energy deficiency and low birth weight consistently show positive associations with stunting across most areas, although with varying strengths. In contrast, access to improved sanitation demonstrates a strong negative association, while exclusive breastfeeding and improved drinking water display spatially heterogeneous and, in some areas, paradoxical positive coefficients. These patterns highlight that the determinants of stunting are context-specific and underscore the importance of geographically targeted nutrition, water, and sanitation interventions rather than uniform policy approaches.

3.2.1. Spatial analysis of the CED among pregnant women

Based on Figure 3(a), the geographically weighted regression of stunting risk factors as a predicted model of CED analysis results, CED among pregnant women exhibits a consistently positive association with stunting prevalence across all regions. Local coefficient estimates range from 0.00117 to 0.00168, with the highest values concentrated in the southern part of Central Java, including Magelang, Magelang City, Klaten, Sukoharjo, and Wonogiri. In these areas, a 1% increase in the proportion of pregnant women with CED is associated with an increase in stunting prevalence of approximately 0.00158-0.00168%.

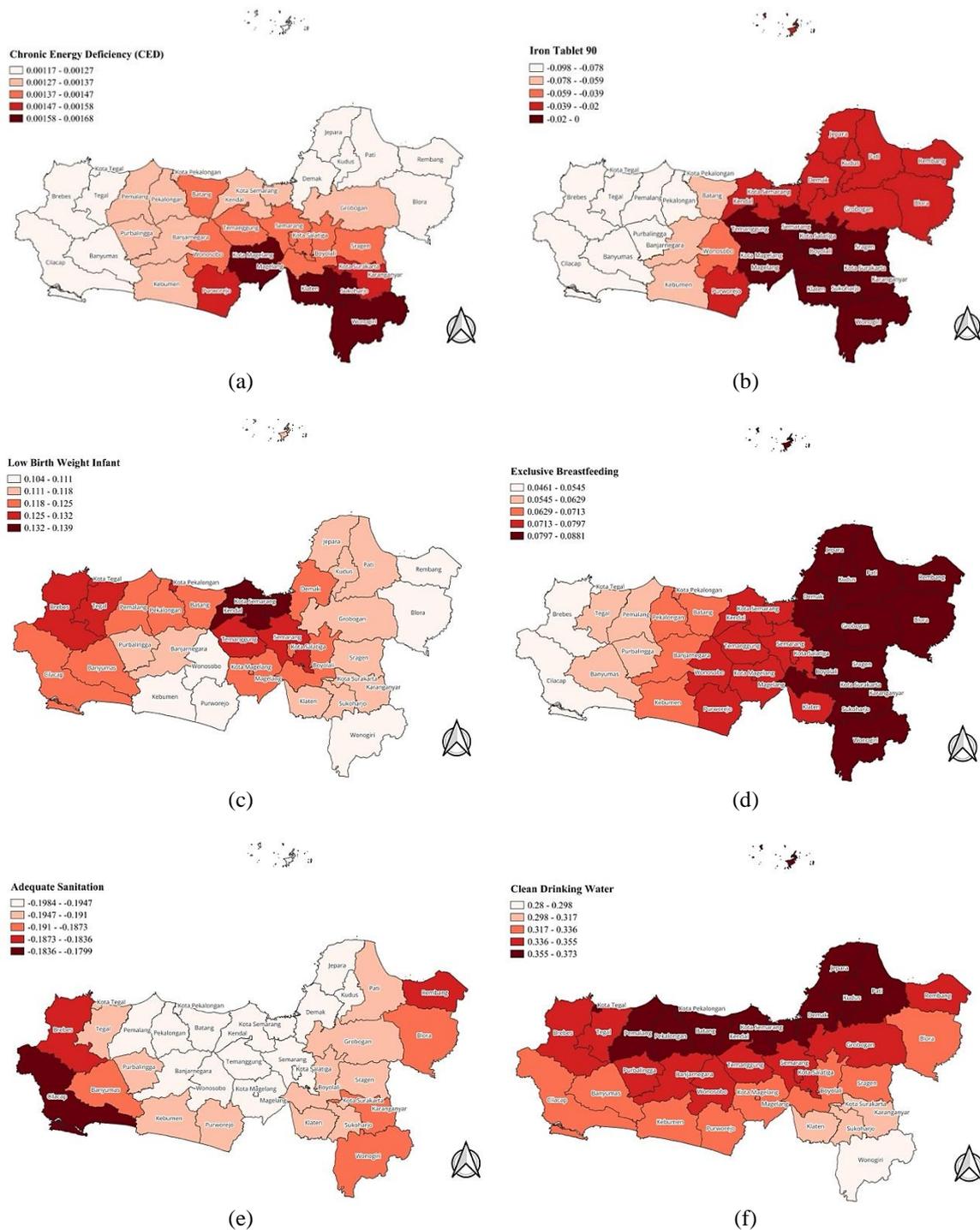


Figure 3. Geographically weighted regression of stunting risk factors as predicted model analysis of (a) CED, (b) iron supplementation (≥ 90 tablets), (c) LBW infant, (d) exclusive breastfeeding, (e) access to improved sanitation, and (f) access to improved drinking water

At the provincial level, a 1% increase in CED is associated with an approximate 0.0014% increase in stunting prevalence, indicating that maternal nutritional status during pregnancy remains an important determinant of child stunting, although the absolute effect size is relatively modest. This finding is consistent with biological evidence demonstrating that maternal undernutrition during pregnancy can impair fetal growth, including bone ossification processes that begin early in gestation and continue until birth [15]. Moreover, prior studies suggest that nutritional counseling interventions for pregnant women can significantly reduce the risk

of stunting after adjusting for sociodemographic and environmental factors (OR: 0.75; 95% CI: 0.60–0.94; $p = 0.012$) [14].

Accumulating evidence further indicates that maternal CED often originates during adolescence. Adolescent girls experiencing CED have a substantially higher risk of anemia compared with those without CED (OR = 5.21; 95% CI: 1.01–26.83; $p = 0.048$) [16]–[18]. Consequently, the observed spatial variation in CED reflects underlying structural disparities across regions and highlights the need for region-specific, life-course-based nutritional interventions.

3.2.2. Spatial analysis of the iron supplementation (≥ 90 tablets)

Based on Figure 3(b), the geographically weighted regression of stunting risk factors as predicted model analysis results of iron supplementation (≥ 90 tablets), coverage of iron supplementation demonstrates a negative association with stunting prevalence in nearly all regions. Local coefficients range from -0.098 to 0, with the strongest protective effects observed in western Central Java, including Brebes, Tegal City, Tegal, Pemalang, Pekalongan, Pekalongan City, Purbalingga, Banyumas, and Cilacap. In these districts, a 1% increase in iron supplementation coverage is associated with a 0.078–0.098% reduction in stunting prevalence.

On average, a 1% increase in iron supplementation coverage at the provincial level corresponds to a 0.028% decrease in stunting prevalence. This spatial variation suggests that the effectiveness of iron supplementation programs is context-dependent and influenced by local adherence and baseline anemia burden. These findings are consistent with studies from low- and middle-income countries reporting spatial clustering of adherence to iron supplementation among pregnant women [19], [20]. Evidence from South Asia indicates that consumption of ≥ 120 iron tablets during pregnancy is associated with a 14% reduction in stunting risk, while in Nepal, consumption of at least 90 tablets before or by the sixth month of pregnancy reduced stunting risk by 23% [21], [22]. Furthermore, iron supplementation combined with other maternal health interventions has been shown to reduce anemia, low birth weight, and childhood stunting [23]. A bidirectional relationship between iron deficiency anemia and stunting has also been documented [24].

3.2.3. Spatial analysis of the LBW

Based on Figure 3(c), the geographically weighted regression of stunting risk factors as predicted model analysis results of LBW shows a strong and consistent positive association with stunting prevalence across all regions. Local coefficients range from 0.104 to 0.139, with a median value of 0.118. The highest coefficients are observed in Kendal and Semarang City, where a 1% increase in LBW prevalence is associated with a 0.132–0.139% increase in stunting prevalence.

These findings confirm LBW as one of the most influential determinants of stunting, reflecting the cumulative impact of nutritional and health risks during the prenatal period. This result aligns with geospatial studies from the United States identifying spatial clusters of LBW and prematurity, as well as meta-analytical evidence from low and middle-income countries demonstrating that LBW more than doubles the risk of stunting (OR: 2.32; 95% CI: 2.05–2.62) [25], [26]. Similar spatial patterns have also been reported in West Africa using Bayesian spatial modeling approaches [27]. Children born with LBW consistently exhibit a substantially higher prevalence of stunting compared with those born at normal birth weight [28], [29].

3.2.4. Spatial analysis of the exclusive breastfeeding

Based on Figure 3(d), the geographically weighted regression of stunting risk factors as predicted model analysis results of exclusive breastfeeding, a paradoxical finding emerges for exclusive breastfeeding, which displays positive coefficients across all regions, ranging from 0.039 to 0.089 (median 0.070) in Table 3. Higher coefficients are observed in eastern Central Java, including Jepara, Pati, Demak, Grobogan, Blora, Rembang, Kudus, Boyolali, Sragen, Surakarta, Karanganyar, Sukoharjo, and Wonogiri, where a 1% increase in exclusive breastfeeding coverage is associated with a 0.046–0.055% increase in stunting prevalence. This finding contradicts established nutritional theory and a robust body of global empirical evidence consistently demonstrating that exclusive breastfeeding during the first six months of life is protective against linear growth faltering in children.

Nevertheless, this positive association should not be interpreted as causal, but rather as reflecting the influence of confounding factors and potential effect modification. Biologically, the benefits of exclusive breastfeeding for child growth are strongly dependent on maternal nutritional status, including adequate intake of key micronutrients such as zinc and iron, which directly influence the nutritional composition of breast milk. Maternal micronutrient deficiencies, which are common in low- and middle-income settings, may compromise breast milk quality and limit the nutrients available for optimal infant growth, even when breastfeeding is practiced exclusively [30].

In addition, inadequate complementary feeding practices (CF) after six months of age represent an important mechanism that may explain this paradoxical association. Systematic evidence indicates that delayed, insufficient, or low-quality complementary feeding is frequently associated with impaired linear

growth among children under two years of age, even when exclusive breastfeeding was provided during early infancy [31].

Taken together, these paradoxical findings underscore that the promotion of exclusive breastfeeding alone is insufficient to reduce stunting prevalence if not accompanied by improvements in maternal nutritional status, timely and high-quality complementary feeding education, and adequate environmental and food support within the local socioeconomic context.

3.2.5. Spatial analysis of the access to improved sanitation

Based on Figure 3(e), the geographically weighted regression of stunting risk factors as predicted model analysis results of improved sanitation, access to improved sanitation shows a strong and consistent negative association with stunting prevalence. Local coefficients range from -0.238 to -0.174, with a median of approximately -0.198. In districts including Pemalang, Pekalongan, Batang, Kendal, Semarang City, Demak, Jepara, Kudus, Magelang, Temanggung, Wonosobo, and Banjarnegara, a 1% increase in access to improved sanitation is associated with a 0.195-0.198% reduction in stunting prevalence.

These results are consistent with evidence indicating that children living in households with improved sanitation are significantly less likely to be stunted [32]. In contrast, children without access to safely managed sanitation face nearly a threefold higher risk of stunting [33]. Longitudinal evidence from multiple countries further supports the role of improved sanitation in stunting prevention [34].

3.2.6. Spatial analysis of the access to improved drinking water

Based on Figure 3(f), the geographically weighted regression of stunting risk factors as predicted model analysis results of the access to improved drinking water, access to improved drinking water shows a positive coefficient, ranging from 0.184 to 0.395, with a median of approximately 0.301 shown in Table 3. This indicates that a 1% increase in coverage of improved drinking water is associated with a 0.30% increase in stunting prevalence. The highest coefficients are observed in northern Central Java, including Pemalang, Pekalongan, Batang, Kendal, Semarang City, Demak, Jepara, Kudus, and Pati.

The positive association observed between access to improved drinking water and stunting prevalence in this study may reflect a discrepancy between the administrative classification of “improved” water sources and the actual microbiological safety of the water consumed. Although sources such as piped water, protected wells, or hand-pumps are considered improved, household drinking water contaminated with enteric pathogens, including *Escherichia coli* has been shown to significantly increase the probability of stunting and undernutrition in children under five, pointing to the inadequacy of source classifications alone as measures of safety. In a large multi-country analysis, children from households with *E. coli*-contaminated water had a 2.3 percentage-point higher probability of being stunted compared with those with uncontaminated water [35].

Systematic evidence further indicates that microbiological contamination of drinking water is a key risk factor for stunting, as recurrent enteric infections and diarrhoea can impair nutrient absorption and contribute to chronic undernutrition [36]. Additionally, studies in Indonesia found that microbiologically contaminated household drinking water was strongly associated with a higher risk of stunting, even when chemical contaminants were within acceptable limits [37]. These findings suggest that expanding coverage of improved drinking water alone may be insufficient to reduce stunting risk without ensuring water safety at the point of use, underscoring the need for direct water quality assessment and integrated water, sanitation, and environmental health interventions.

4. CONCLUSION

This study demonstrates substantial spatial heterogeneity in the determinants of stunting across districts in Central Java, highlighting the added value of Geographically Weighted Regression for uncovering localized relationships that are obscured in global models. The findings provide novel empirical evidence that key nutrition and environment-related factors, including maternal chronic energy deficiency, low birth weight, sanitation, exclusive breastfeeding, and access to improved drinking water, exert spatially varying effects on stunting prevalence. These results underscore the importance of territorially targeted nutrition and environmental health policies rather than uniform interventions. The paradoxical associations observed for exclusive breastfeeding and improved water access further emphasize the need to move beyond coverage indicators toward assessments of maternal nutrition, complementary feeding practices, and water safety. This study is limited by its cross-sectional design and reliance on secondary aggregated data, which preclude causal inference. Future research should incorporate longitudinal data, direct water quality measurements, and individual-level nutrition indicators to better inform spatially tailored stunting prevention strategies.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

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

ETHICAL APPROVAL

This study is based entirely on secondary data that are publicly available and do not contain any personal or identifiable information. The data sources include official publications from government and aggregate statistical data (not individual-level data). The research did not involve any direct intervention with human participants or animals, and no primary data collection from research subjects was conducted. Therefore, ethical approval was not required.

DATA AVAILABILITY

The data that support the findings of this study are openly available at the following sources:

- https://dinkesjatengprov.go.id/v2018/dokumen/1Profil_Kesehatan_2023/files/downloads/Profil%20Kesehatan%20Jawa%20Tengah%202023.pdf.
- <https://jateng.bps.go.id/id/statistics-table/3/VGtGTU5qbDFIQz1lVWxCTVNWZEIXbWRhWkUwMFVUMDkjMw==/persentase-rumah-tangga-yang-memiliki-akses-terhadap-sanitasi-layak-menurut-kabupaten-kota-di-provinsi-jawa-tengah--2023.html?year=2023>.

These datasets are publicly accessible and were obtained from official government publications.

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