

Spatial Determinants of Environmental Quality in Central Java, Indonesia: Evidence from a Geographically Weighted Regression Approach

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Abstract

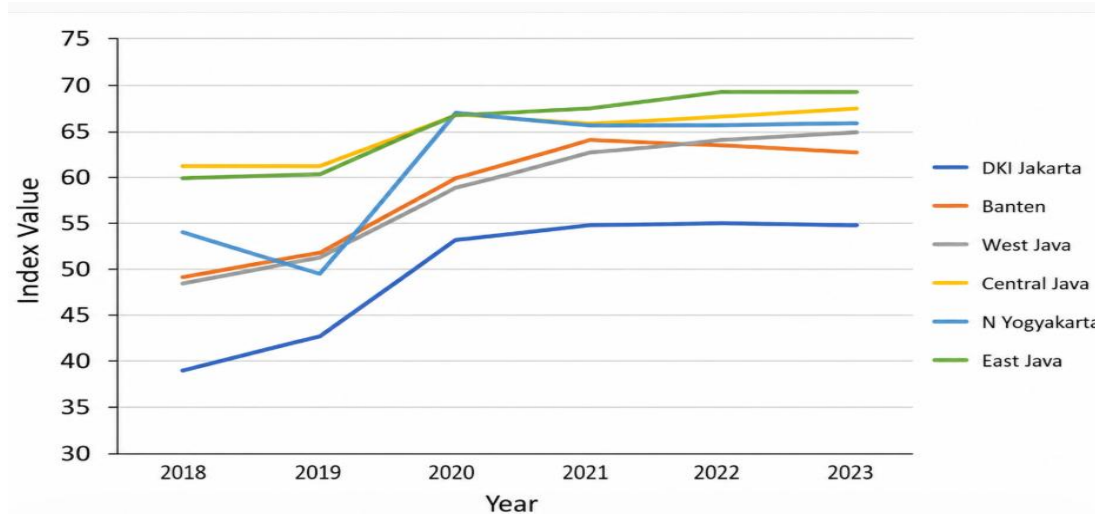
Central Java Province, the fifth most populous province in Indonesia, with a density of 1,113 people per km², faces mounting pressure on environmental quality despite moderate current conditions. This study aims to examine the spatial influence of poverty, Human Development Index (HDI), and rice productivity on the Environmental Quality Index (EQI) across regencies and cities in Central Java in 2023. The uniqueness of this research lies in the use of the Geographically Weighted Regression (GWR) model, which enables a spatially nuanced analysis beyond conventional global regression, thereby capturing regional variations more accurately. In the long term, this approach can support the formulation of more targeted and region-specific environmental policies. The study employs a quantitative approach using secondary data from regencies and cities in Central Java, analyzed through the GWR model. The results indicate that the effect of poverty on the Environmental Quality Index is spatially uneven, with three regions showing a significant negative relationship while the other 32 regions show no significant effect. HDI exhibits mixed influences: seven regions demonstrate significant relationships, consisting of one positive and six negative, while 28 regions remain insignificant. Rice productivity also displays spatial variability, with three regions showing significant positive effects, one region showing a negative effect, and most regions showing insignificant. These findings highlight the importance of adopting adaptive and spatially-informed environmental management strategies. Policies should integrate poverty reduction with environmental protection, strengthen human development through environmental literacy, and encourage sustainable agricultural practices. Such measures are essential to improve environmental quality in Central Java while balancing the challenges of high population density and rapid economic growth.

Keywords: Poverty; HDI; Rice; Productivity; EQI; GWR

1. Introduction

Environmental quality is one of the important indicators in determining the level of sustainable development in a region (Heffi, 2023).

However, environmental quality in Indonesia, especially in the province of Central Java, still faces significant challenges due to various economic, social, and human activity factors (Rahmi et al., 2025). Central Java Province, as one of the provinces with a high population density of 1,113 people per km² and ranked as the fifth most densely populated province in Indonesia, is facing various complex environmental problems (Rosyadi et al., 2023). This density exacerbates environmental problems such as water pollution, land conversion, and natural resource degradation.



Source : MoEF Performance Report, 2023

Figure 1. Environmental Quality Index Data on Java Island in 2018-2023

Based on data from the 2023 Performance Report of the Ministry of Environment and Forestry (MoEF), the average Environmental Quality Index (EQI) for Central Java Province was 68.59, which is still below the national average of 72.54. This condition indicates that the environmental quality in Central Java is still moderate and requires serious attention from various development sectors.

One of the main factors affecting environmental quality is poverty. Poor communities tend to have limited access to resources, environmentally sustainable technology, and education, making them more dependent on direct exploitation of nature to meet their needs. Activities such as illegal land clearing, tree felling, and the use of non-environmentally sustainable fuels are often carried out without considering their impact on environmental sustainability. Research by Rachmawati et al., (2021) 'The influence of access to proper sanitation, poverty and population on the Environmental Quality Index on Sumatra Island in 2018–2022', shows that poverty and population size have a negative impact on the Environmental Quality Index, meaning that the higher the poverty rate, the more environmental quality decreases. However, (Nengsih et al., 2023) presents different findings, suggesting that poverty has a positive and significant impact on EQI. This discrepancy indicates that the impact of poverty on environmental quality can vary depending on the regional context, control variables, and methodological approaches used in the research.

In addition to poverty, the agricultural sector, particularly rice productivity, also plays an important role in environmental quality dynamics. As an agricultural province, Central Java relies heavily on rice production as its leading sector. However, the high productivity that farmers strive to achieve often encourages the excessive use of chemical inputs such as fertilizers and pesticides. The long-term use of these substances can contaminate groundwater, reduce soil

fertility, and increase greenhouse gas emissions from the agricultural sector (Srivastav et al., 2024). In addition, agricultural intensification without wise management has caused ecological degradation in many areas. Therefore, although the agricultural sector contributes significantly to economic growth, its impact on environmental quality needs to be analyzed comprehensively.

The third influential factor is the Human Development Index (HDI), which reflects the level of development achievement in terms of education, health, and income. Research by (Matusiewicz, 2025) found that the Human Development Index (HDI) has a significantly positive effect on the Environmental Quality Index (EQI) in Java. In contrast, (Ferraz et al., 2025) reported that inequality, as proxied by the HDI, negatively affects environmental quality. These inconsistencies suggest that social development factors can influence the environment in complex and sometimes contradictory ways.

The relationship between poverty, rice productivity, and the Human Development Index (HDI) with environmental quality in Central Java Province varies from region to region. Each district or city has unique social, economic, and geographical conditions. Therefore, this study uses the Geographically Weighted Regression (GWR) method, which can more accurately observe the differences in the influence of these variables in each region. This method is superior to conventional statistical methods because it can show how the relationships between variables differ in different places, making the results more useful for formulating policies tailored to the needs of each region.

Although many previous studies have examined the relationship between social, economic, and environmental factors, most still use a general approach that pays little attention to differences in characteristics between regions. Traditional statistical methods are often unable to capture the spatial diversity that exists in each district or city. Central Java Province itself is very diverse in terms of geography, economy, and society, so that each region's response to factors such as poverty, HDI, and agricultural activities can be very different. Therefore, this study seeks to provide a more accurate understanding of local conditions and provide a more appropriate basis for environmental policies that can be adapted to the circumstances of each region. This spatial-based approach is essential for addressing the challenges of sustainable development today and in the future.

The environmental quality in Central Java remains below the national average and is increasingly threatened by interrelated factors such as poverty, agricultural practices, and disparities in human development. Previous studies have produced inconsistent findings regarding the effects of poverty and human development on environmental quality, while the role of agricultural productivity has often been examined without adequate attention to its long-term ecological implications. Moreover, most prior research employed conventional statistical methods that assume regional homogeneity, thereby neglecting the importance of spatial heterogeneity across regencies and cities. To address this gap, the objective of this study is to analyze the spatial relationship between poverty, rice productivity, and the Human Development Index (HDI) on environmental quality in Central Java Province by applying the Geographically Weighted Regression (GWR) method. The contribution of this research is both theoretical, by offering new insights into the spatial dynamics that determine environmental quality, and practical, by providing empirical evidence for policymakers to design region-specific strategies for sustainable development. The novelty of this study lies in its application of the GWR model, which captures localized variations in the effects of poverty, agricultural productivity, and human development on environmental quality, thus producing more robust and policy-relevant insights to improve environmental outcomes at the regional level.

Accordingly, this study formulates a set of research questions that respond to the empirical and methodological gaps in the existing literature, which has largely relied on global regression models and treated regions as spatially homogeneous. First, what is the effect of

poverty on the Environmental Quality Index (EQI) in the regencies and cities of Central Java Province, a densely populated region whose environmental quality remains below the national average? Second, how does the Human Development Index (HDI) affect the EQI in these same areas, given previous studies' inconsistent findings on the HDI–environment nexus? Third, to what extent does rice productivity as a key agricultural activity influence the EQI across regencies and cities, particularly in a province where rice is both an economic backbone and a potential ecological pressure? Finally, in what ways does the application of the Geographically Weighted Regression (GWR) method, as a spatially explicit approach, reveal local variations in these effects that are obscured by conventional global models, thereby providing more precise evidence for designing region-specific environmental and development policies in Central Java Province?

2. Literature Review

2.1 Poverty and Environmental Quality: Theoretical Background and Empirical Evidence

The relationship between poverty and environmental quality is rooted in classical development theory, which argues that poverty constrains households' ability to adopt environmentally sustainable practices. Poor communities often lack access to clean energy, proper sanitation, and environmentally friendly technology, making them more reliant on direct natural resource extraction to meet daily needs. This condition intensifies environmental degradation through activities such as illegal land clearing, reliance on low-quality fuels, and unmanaged waste disposal. The theory suggests a negative association between poverty and ecological well-being, particularly in regions with high population density and limited governance capacity.

Environmental quality is strongly embedded in the grand framework of Sustainable Development Theory, which emphasizes that true development requires a balance between economic growth, social welfare, and environmental preservation (Ghosh & Pearson, 2025; Mendonça et al., 2025). The Environmental Kuznets Curve (EKC) hypothesis further supports this perspective by suggesting that in the early stages of development, economic growth tends to worsen environmental conditions, but beyond a certain threshold, higher income and human development may contribute to ecological improvements (Gupta et al., 2025). On one hand, this thesis implies that socioeconomic progress, such as poverty reduction and human development, can eventually improve environmental quality. On the other hand, critics of EKC argue that the pattern is not universal, as in many developing regions, rising welfare instead increases consumption, industrialization, and agricultural intensification, which harm the environment (Agusalim et al., 2025; Yilmaz et al., 2025). Synthesizing these perspectives, this study departs from the assumption that the relationship between development and environmental quality in Central Java is not linear, but rather shaped by local contexts of poverty, agricultural practices, and human development disparities. From this foundation, the first hypothesis is that poverty has a significant effect on the Environmental Quality Index (EQI) in Central Java Province.

The nexus between poverty and the environment has long been debated within the framework of Environmental Scarcity Theory and the Poverty–Environment Trap Hypothesis. These perspectives argue that poverty compels communities to exploit natural resources directly for survival, leading to environmental degradation such as deforestation, soil erosion, and pollution (Rashid et al., 2025; Requena-i-Mora et al., 2025). Empirical evidence supports this thesis, where studies in developing countries confirm that higher poverty levels correlate with lower environmental quality due to unsustainable livelihood practices (Cui et al., 2025; Rashid et al., 2025). However, an antithesis view suggests that environmental degradation is not exclusively linked to poverty, as wealthier communities may consume more resources and generate higher emissions, thereby worsening environmental conditions (Kelly & Nembot Ndeffo,

2025; Nachibi & Morgan, 2025). The synthesis of these arguments reveals that the relationship between poverty and environmental quality is context-dependent, requiring careful spatial analysis. Based on this confrontation of theories, the second hypothesis of this study states that higher poverty levels are associated with lower environmental quality in the regencies and cities of Central Java Province.

Empirical studies provide mixed evidence. Ghosh & Pearson, (2025); Mendonça et al., (2025) find that poverty contributes to lower Environmental Quality Index (EQI) values, reinforcing the theoretical expectation that limited access to resources exacerbates environmental degradation. Conversely, Cui et al., (2025); Rashid et al., (2025) report a positive and significant association between poverty and EQI, suggesting that the poverty–environment linkage depends heavily on local socio-economic dynamics and the structure of livelihoods. These contrasting findings underscore the contextual nature of the poverty–environment nexus and highlight the need for geographically sensitive methods.

H1: Poverty has a significant effect on the Environmental Quality Index (EQI) in regencies/cities of Central Java Province.

2.2 Human Development Theory and Its Implications for Environmental Sustainability

Human Development Theory posits that improvements in education, health, and income empower individuals to achieve a better quality of life and potentially adopt environmentally responsible behavior (Bahr et al., 2025; UNDP, 2023). The thesis view argues that higher Human Development Index (HDI) levels enhance environmental awareness, encourage sustainable practices, and improve community engagement in ecological protection. In this perspective, development enhances capacity for environmental stewardship.

However, the antithesis argues that increases in HDI, especially income and consumption, may worsen environmental quality through expanding material demand, accelerating urbanization, and increasing energy use (Al-Maadid et al., 2025; Luo et al., 2025). This suggests that the HDI–environment relationship is not linear and may shift depending on institutional capacity, urban characteristics, and development patterns.

The role of human development in environmental sustainability is explained by Human Development Theory, which emphasizes that improvements in education, health, and income empower individuals to achieve higher quality of life and adopt sustainable practices (Bahr et al., 2025; UNDP, 2023). In line with this thesis, several studies argue that a higher Human Development Index (HDI) leads to better environmental quality, as educated and healthier populations are more aware of ecological issues and support sustainable innovations (Kumar et al., 2025; Polat & Çil, 2025). Conversely, the antithesis claims that increases in HDI can also exacerbate environmental degradation by stimulating higher consumption, urban expansion, and energy use, particularly in regions where economic growth relies on resource-intensive sectors (Al-Maadid et al., 2025; Luo et al., 2025). Synthesizing these opposing views, the effect of HDI on environmental quality is not uniform, but varies across regions depending on institutional capacity and cultural practices. This leads to the third hypothesis that HDI has a significant effect on the Environmental Quality Index (EQI) in Central Java Province.

Previous empirical findings also display variation. Kumar et al., (2025); Polat & Çil, (2025) find that higher HDI is associated with improved environmental indicators, while other studies document negative or mixed effects in rapidly urbanizing economies. These inconsistencies indicate that environmental outcomes of human development differ across space and require a spatially explicit analytical approach.

H2: The Human Development Index (HDI) significantly affects the Environmental Quality Index (EQI) in regencies/cities of Central Java Province.

2.3 Agricultural Intensification Theory and Environmental Outcomes

Agricultural Intensification Theory explains that increases in agricultural productivity especially in staple crops like rice are frequently achieved through greater use of chemical fertilizers, pesticides, and irrigation, which can degrade soil quality, pollute water bodies, and contribute to greenhouse gas emissions (Awan et al., 2025; Pal et al., 2025). This theoretical framework predicts a negative association between agricultural productivity and environmental quality, particularly in regions dominated by traditional, input-intensive farming systems.

Agricultural productivity, particularly rice cultivation, is another determinant of environmental quality that is widely debated within the framework of Agricultural Intensification Theory. According to this theory, increases in productivity are often achieved through greater use of chemical inputs such as fertilizers and pesticides, which may harm the environment by degrading soil quality, contaminating water sources, and contributing to greenhouse gas emissions (Awan et al., 2025; Pal et al., 2025). This thesis is supported by studies showing that intensive rice production reduces ecological sustainability in many developing regions (Jauhari et al., 2025; L. Wang et al., 2025). However, the antithesis offered by proponents of sustainable intensification argues that higher productivity, when managed with ecological principles, can simultaneously enhance food security and environmental outcomes (Radosavljevic et al., 2025; Sariyev et al., 2025). The synthesis suggests that the environmental impact of agricultural productivity depends heavily on farming practices and local management systems. For Central Java, where rice productivity is both an economic priority and a potential ecological burden, the fourth hypothesis of this study is that rice productivity has a significant effect on the Environmental Quality Index (EQI).

Empirical findings support this thesis in many settings. Jauhari et al., (2025); L. Wang et al., (2025) show that intensive rice cultivation contributes to ecological decline. However, contrasting evidence arises from the argument of sustainable intensification proponents, who claim that productivity improvements when combined with modern technology, efficient water management, and environmentally conscious practices can coexist with environmental protection (Radosavljevic et al., 2025; Sariyev et al., 2025). These differing results suggest that environmental impacts are determined not only by output levels but also by the production methods and technological adoption. Given Central Java's reliance on rice as a strategic agricultural commodity, understanding whether productivity harms or supports environmental sustainability is crucial.

H3: Rice productivity significantly affects the Environmental Quality Index (EQI) in regencies/cities of Central Java Province.

2.4 Spatial Heterogeneity and the Need for Geographically Weighted Approaches

Traditional regression models assume homogeneity across regions, but spatial econometrics argues that socio-economic and environmental processes vary geographically. The concept of spatial heterogeneity suggests that the effects of poverty, human development, and agricultural productivity are not constant across space but shift according to local characteristics such as governance quality, urban structure, environmental stresses, and technological adoption.

Previous studies often overlook this spatial complexity by employing global models that mask local variations. In contrast, Geographically Weighted Regression (GWR) enables the examination of location-specific relationships by assigning spatial weights and estimating local parameter coefficients (Pan et al., 2025; Guo et al., 2025; Y. Wang et al., 2025). This method is particularly useful for policy-relevant research where regional disparities play a critical role. Given the diversity of socio-economic and environmental contexts across Central Java's 35

regencies/cities, the application of GWR provides a theoretically consistent approach.

H4: The effects of poverty, HDI, and rice productivity on EQI vary spatially across regencies/cities in Central Java Province (spatial heterogeneity).

3. Methods

3.1 Data description

The type of research used in this study is a quantitative explanatory approach. Quantitative research methods are defined as research methods based on the philosophy of positivism, used to research on certain populations or samples, data collection using research instruments, and statistical data analysis. Explanatory research is research that will explain the relationship between variables that affect the researcher's hypothesis (Gamage, 2025).

Table 1. Data Used in the Study

Variable	Description	Symbol	Unit of Measurement	Data Source
Environmental Quality Index (EQI)	Composite index used to measure environmental quality in each regency/city, covering components such as air, water, and soil quality.	EQI	Index score (%)	Central Statistics Agency (BPS) of Central Java Province, 2023
Poverty Rate	Percentage of population living below the poverty line in each regency/city. Considered a major socio-economic factor influencing environmental pressure.	POV	Percent (%)	BPS Central Java Province, 2023
Human Development Index (HDI)	Composite indicator measuring health, education, and income dimensions to assess human development levels across regions.	HDI	Index score	BPS Central Java Province, 2023
Rice Productivity	Level of rice production per unit area; reflects agricultural intensity and potential environmental pressure from farming practices.	AGRI	Ton/Ha	BPS Central Java Province, 2023
Geographical Coordinates	Longitude and latitude used to capture spatial location of each regency/city for GWR analysis.	(u_i, v_i)	Degrees	Derived from spatial data used in GWR modeling (as referenced in Methods section)
Environmental Features for GWR	Additional spatial characteristics used implicitly in the weighting function for GWR model calibration.	—	—	Constructed within GWR framework based on regional spatial structure (Methods section)

The type of data used in the study is quantitative data. This study uses secondary data,



obtained from the Central Statistics Agency (BPS) of Central Java Province in 2023. This is because the data for that year is up-to-date and has been publicly available. The data used included the percentage of the Environmental Quality Index (EQI), poverty, HDI, and rice productivity level from 35 districts/cities of Central Java Province in 2023 using cross-sectional data. The selection of 35 districts/cities as units of analysis is considered to be able to identify and map differences in geographical effects and socio-economic conditions in each region in more detail and accurately. In addition, statistical data and development indicators in Central Java have also been grouped in each district/city, so that the use of all of these regions facilitates access to data, consistency of processing, and comparisons between regions.

3.2 Methods

GWR (*Geographically Weighted Regression*)

According to Pan et al., (2025) the GWR model is one of the spatial models with a point vector. This model includes the development of the Ordinary Least Square (OLS) linear regression model into a weighted regression model by paying attention to spatial effects, thus producing a parameter estimator that can only be used to predict each point or location where the data is observed and inferred at a certain time (Guo et al., 2025; Y. Wang et al., 2025). The GWR model is a model that pays attention to geographical factors as variables that affect bound variables. The assumption used in the GWR model is that the error is normally distributed with (Omrani et al., 2025; Yu, 2025). In the GWR model the relationship between the Y-bound variable and the independent variable $X_1, X_2, \dots, X_k$ at the i location is (Kuang & Chen, 2025; Rahmila et al., 2025).

$$EQ_i = \beta_0(u_i, v_i) + \beta_1(u_i, v_i) POVi + \beta_2(u_i, v_i) HDI_i + \beta_3(u_i, v_i) AGRI_i + \varepsilon_i \quad (1)$$

$$H_1: \beta_1(u_i, v_i) \neq 0$$

$$H_2: \beta_2(u_i, v_i) \neq 0$$

$$H_3: \beta_3(u_i, v_i) \neq 0$$

$$H_4: \exists i \neq j \text{ such that } \beta_k(u_i, v_i) \neq \beta_k(u_j, v_j), k = 1, 2, 3$$

With, EQ_i represents the Environmental Quality Index in Regencies/Cities in Provinces (i) where $i = 1, 2, \dots, n$. The term (u_i, v_i) denote the geographical location (longitude, latitude) of the Regency/City on Provinsi (i). $POVi, HDI_i, AGRI_i$ are the explanatory independent variables in Regencies/Cities in Provinces (i). $\beta_0(u_i, v_i)$ are the constant/intercept in Regencies/Cities in Provinces (i) and ε_i is the cross-section and term error.

Breusch Pagan Test

Before conducting the analysis with GWR, the Breusch Pagan test was first performed. This test is done to see if the data contains spatial heterogeneity or not. Spatial heterogeneity is indicated by the difference in properties between one location and another. The decision-making criteria of the Breusch Pagan test can also use a comparison of the p-value with α . If p-value is $< \alpha$, then subtract H_0 , so it can be concluded that there is spatial heterogeneity (Kuang & Chen, 2025; Rahmila et al., 2025).

Spatial Autocorrelation Test

Spatial autocorrelation is the correlation between an independent variable and itself. Moran's I test is a local statistical test used to identify the presence of spatial autocorrelation in a location (Chen et al., 2025). The value of the moran index is in the range of $-1 < I < 1$. If $I > I_0$ the data has a positive autocorrelation, while if $I < I_0$, the data has a negative autocorrelation. Moran's I test is defined by the following formula:

$$I = \frac{n \sum_{i=1}^n \sum_{p=1}^n W_{ip} (\chi_i - \bar{\chi})}{\sum_{i=1}^n (\chi_i - \bar{\chi})^2} \quad (2)$$

Weighting Function

The function of the weighter is to provide the results of estimating different parameters at different locations. The selection of spatial weights used in estimating parameters is very important. There are two co Rahmila et al., (2025): Kernel Fixed is the optimal bandwidth value for each location, which is equal or constant. Adaptive Kernel is different bandwidth values for each observation point

Bandwidth Determination

The selection of bandwidth has the impact of determining weights for each observation location in the GWR. The small bandwidth value will result in the resulting variance being larger, so that the model obtained is under-smoothed (Chen et al., 2025; Lee & Park, 2025). The method used in this study is Akaike Information Criterion corrected (AICc). AICc is a method for comparing different models in determining the most suitable model for data. The bandwidth selection method with AICc was carried out by evaluating the smallest AICc value at the maximum and minimum distance intervals of the observation location, so that the minimum AICc value was considered optimal. Systematically, AICc can be written:

$$AICc = 2n1n(\hat{\sigma}) + n \ln(2n) + n \left\{ \frac{n+tr(L)}{n-2-tr(L)} \right\} \quad (3)$$

GWR Model Parameter Estimation

The parameters of the GWR model were estimated using the Weighted Least Square (WLS) method, which gave different weights to each observation location and in accordance with Tobler's Law I: "Everything is interconnected, but something close has more influence than something far away". In the GWR model, the weights at each observation site represent the distance from the observation site to another observation site. So the parameters at the observation location $((u_i, v_i)(u_i, v_i) u_i, v_i)$ are assumed to be minimized (Chen et al., 2025):

$$\sum_{i=1}^n W_{ij}(u_i, v_i) \varepsilon_i^2 = \sum_{i=1}^n W_{ij}(u_i, v_i) [y_i - \beta_0(u_i, v_i) - \sum_{k=1}^p \beta_k(u_i, v_i) \chi_{ik}]^2 \quad (4)$$

GWR Model Conformity and Parameter Testing

The suitability test of the GWR model is carried out to test the statistics of the effect of the weighting function or to find out the geographical variables affecting the GWR model. A hypothesis decision of zero is accepted if $F_{cal} < F_{table} (\alpha; df1; df2)$ means that there is no significant geographical influence on the model and the null hypothesis is rejected if $F_{cal} \geq F_{table} (\alpha; df1; df2)$ means that there is an influence of geographical factors on the model. The test uses a statistical test to determine which independent variables have a significant impact on the dependent variables at each location (Lu et al., 2025; Yu et al., 2025).

4. Results

GWR (Geographically Weighted Regression)

The first step before performing the GWR analysis, the BP (Breusch-Pagan) test analysis was first carried out to test the spatial heterogeneity. Which is needed to accommodate spatial heterogeneity by proving the local coefficient or difference in properties between one location and another. The results obtained through data processing through the GeoDa spatial application software with the Spatial Lag model, obtained a BP p-value test value of 0.05716. The concept of the Spatial Lag Model considers the effect of spatial dependence between regions on dependent variables from the surrounding region. With a p-value ratio of less than $\alpha = 0.10$ (10% significance), it can be concluded that there is spatial heterogeneity or regional diversity in the model. When there is an aspect of spatial heterogeneity or passes the BP test, the GWR analysis can be continued. Next, an analysis of Moran's I test or Moran Index was carried out to

test the value of its spatial autocorrelation, as shown in the following figure:

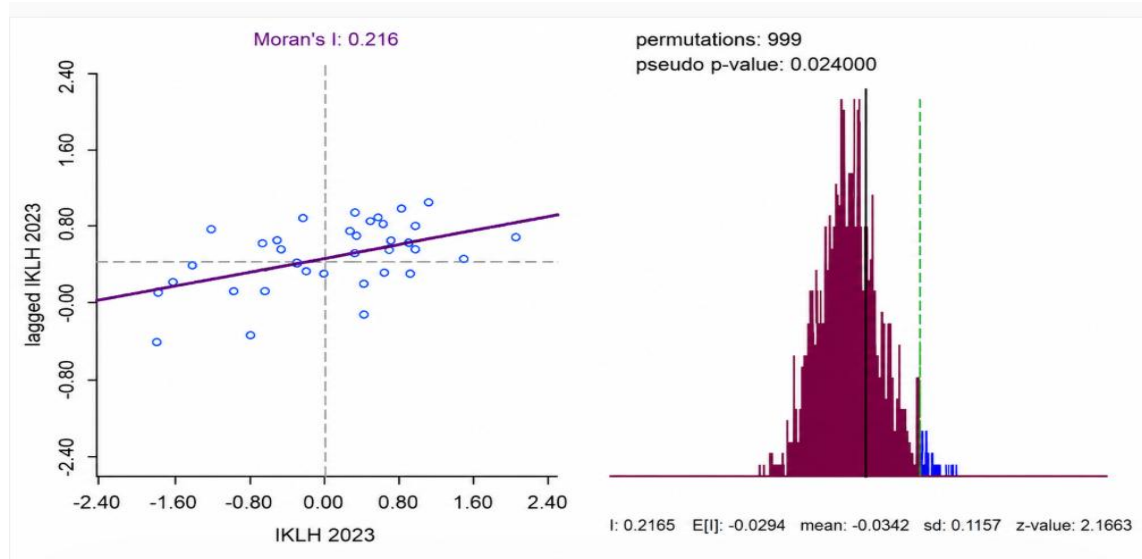


Figure 2. Results of Moran's I Test Analysis

In figure 2, explained about the results of data processing from GeoDa, the Moran Index test value was obtained at 0.216 which was tested with a value of $I_0 = -0.0294$. Because the value of Moran's test value is greater than I_0 , it can be concluded that there is a positive autocorrelation, which means that the quality of the environment in Central Java that is good or bad tends to be close to each other (Lu et al., 2025; Yu et al., 2025). In the development of the GWR model, the first stage is to determine the geographical location of each Regency/City in Central Java. The next stage, with calculations through the GWR4 application software, is the selection of a Fixed Gaussian Kernel to describe the spatial relationship between flexible variables, since the value of the bandwidth data used is constant or equal. Furthermore, to determine the optimal bandwidth, the Golden Section Search technique is used, which aims to minimize the Cross Validation (CV) value. This process ensures that the bandwidth used will provide the most accurate estimate results and match the available spatial data. Based on the final output results from GWR, the classic global regression model for the Environmental Quality Index in Central Java in 2023 is obtained as follows:

$$\text{Environmental Quality Index} = 64.530792 + 0.525243\text{POV} - 0.163859\text{HDI} + 0.104977\text{AGRI}$$

In the model, a significant influence parameter was obtained in the global regression model with $\alpha = 10\%$ which included two significant variables for the Environmental Quality Index (IKLH) in Central Java, namely Intercept (IKLH) and Poverty Level (POV). Thus, the GWR model for IKLH in Central Java can be written as follows:

$$\text{Environmental Quality Index} = 64.530792 + 0.525243\text{POV} \quad (5)$$

The interpretation of the model is:

1. Assuming other variables are constant, every single unit change in the poverty level (POV) will affect a change in the Environmental Quality Index (EQI) of 0.525243%.
2. HDI and Rice Productivity (AGRI) are not statistically significant, so the two variables do not affect the change in EQI at the level of significance set in the GWR model.

After knowing the results of the analysis of the global regression model, the next step is to test the conformity parameters of the GWR model which aims to analyze what factors can affect Environmental Quality Index in Central Java Province in 2023. This testing of the conformity of the GWR Fixed Gaussian model is very important to understand the spatial variability present in the IKLH data, which cannot be fully explained by a global regression model that only provides an average estimate without considering differences between regions. Here's a test to assess the spatial variation of its local coefficients:

Table 2. GWR Fixed Gaussian Model Conformity Testing

Variable	F	DOF	For F Test	Diff of Criterion	Description
Intercept	252.468943	2.931	2.000	-108963963008723.000000	Significant
Poverty	32.533387	1.654	2.000	-108963963009259.000000	Significant
HDI	52.331163	2.140	2.000	-108963963008957.000000	Significant
Rice Productivity	1525.202492	2.405	2.000	-108963963008956.000000	Significant

Table Results. 1. The Diff of Criterion shows that all variables have negative values, meaning that there is spatial variability in terms of model selection criteria. Here is a comparison of the indicators between AICc, AIC and R2 of the model:

Table 3. Comparison of Indicators

Model	R2	AIC	AICc
Classic Global Regression	0,327589	187,242032	189,310997
GWR Fixed Gaussian	0,988776	101,994175	-108963963007740,000000

Based on the R2, AIC and AICc indicators, it can be concluded that the Fixed Gaussian kernel-type GWR regression model is a better model than the classic global regression model, because the R2 results are larger and the AIC and AICc values are smaller. Which means that the 98.88% Gaussian GWR Rsquare in the Environmental Quality Index variation can be explained in the model. The results of the GWR model estimation in each Regency/City of Central Java in 2023 have significant spatial variability results on the influence of independent variables (POV, HDI, AGRI) on different bound variables (EQ) in each region. One example of a model in Kebumen Regency shows:

$$\text{EQ of Kebumen Regency} = -0.853 + 1.703\text{HDI}$$

It is interpreted that every increase of one unit of the Human Development Index (HDI) will significantly reduce the IKLH value by 1,703 because it has a negative effect, while poverty (POV) is not included in this model because it is insignificant.

To clearly present the empirical outcomes, the following table summarizes the significance of the GWR results for Poverty (POV), Human Development Index (HDI), and Rice Productivity (AGRI) on the Environmental Quality Index (EQI) across 35 regencies/cities in Central Java Province.

Table 4. Summary of GWR Significance Results Across Regions

Variable	Significant Positive Effect	Significant Negative Effect	No Significant Effect	Hypothesis Alignment
Poverty (POV)	0	3 (Semarang Regency, Kendal Regency, Semarang City)	32	Supports H ₁ (partial; negative but spatially varied)
HDI	1 (Kebumen Regency)	6 (Semarang Regency, Temanggung, Kendal, Pemalang, Salatiga City, Semarang City)	28	Supports H ₂ (mixed effects; context-dependent)
Rice Productivity (AGRI)	3 (Semarang Regency, Semarang City, Kendal Regency)	1 (Rembang Regency)	31	Supports H ₃ (mixed; sustainable vs. traditional farming)
Spatial Variation	-	-	-	Fully supports H ₄ (clear spatial heterogeneity detected)

To complement Table 4, Table 5 reports the specific values of poverty rates, HDI scores, rice productivity, and EQI for the regions where significant relationships were identified. These data are sourced from BPS Central Java (2023) and SISKLHK (2023).

Table 5. Variable Values in Regions with Significant Relationships (Poverty, HDI, Rice Productivity, and EQI), Central Java, 2023

Region	Poverty Rate (%)	HDI Score	Rice Productivity (quintals/ha)	EQI Score	Type of Relationship
Significant negative relationship (Poverty → EQI)					
Semarang Regency	7.17	-	-	-	Negative
Kendal Regency	9.39	-	-	-	Negative
Semarang City	4.23	-	-	-	Negative
Significant positive relationship (HDI → EQI)					
Kebumen Regency	16.34	71.37	-	73.92	Positive
Significant negative relationship (HDI → EQI)					
Semarang Regency	-	75.13	-	-	Negative
Temanggung Regency	-	71.33	-	-	Negative
Kendal Regency	-	73.86	-	-	Negative
Pemalang Regency	-	68.03	-	-	Negative

Region	Poverty Rate (%)	HDI Score	Rice Productivity (quintals/ha)	EQI Score	Type of Relationship
Salatiga City	-	84.99	-	-	Negative
Semarang City	-	84.43	-	-	Negative
Significant positive relationship (Rice Productivity → EQI)					
Semarang Regency	-	-	53.9	-	Positive
Kendal Regency	-	-	53.75	-	Positive
Semarang City	-	-	57.58	-	Positive
Significant negative relationship (Rice Productivity → EQI)					
Rembang Regency	-	-	56.35	-	Negative
Examples of non-significant regions (for comparison)					
Surakarta City	-	83.54	-	62.65-63.43	Not significant
Jepara Regency	-	-	49.26	-	Not significant

Note: A dash (–) indicates that the variable was not statistically significant in that specific relationship or that the data are not reported for that context.

Additional descriptive insights: Kebumen Regency recorded an EQI of 73.92, which is above the national average, despite its relatively high poverty rate (16.34%). Surakarta City, with a high HDI of 83.54, exhibited a moderate EQI ranging from 62.65 to 63.43, with component scores of 83.06 for air quality, 50.98 for surface water quality, and 30.22 for land cover quality. Jepara Regency had a rice productivity of 49.26 quintals/ha, but the industrial sector dominates its economy (34.45% of GRDP), potentially overshadowing the agricultural impact on environmental quality.

Spatial Visualisation of Significance

The spatial distribution of significant relationships for each variable is presented in Figures 3–5.

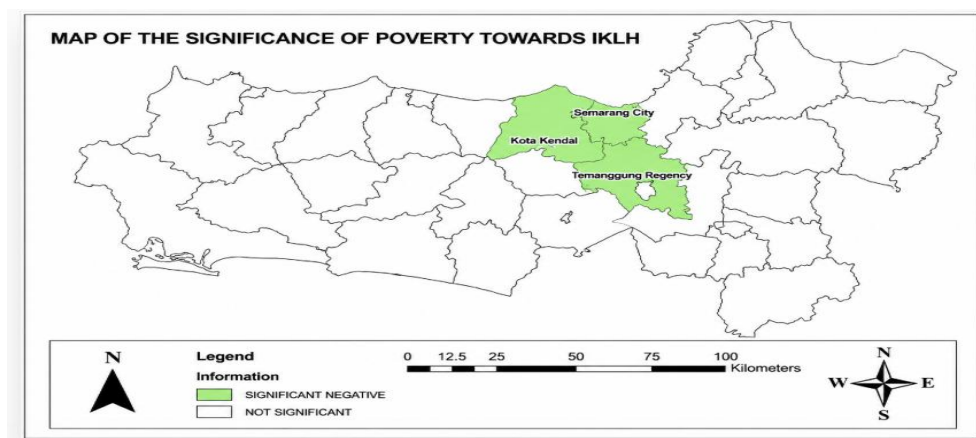


Figure 3. Significance of the effect of poverty on the Environmental Quality Index (EQI) across 35 regencies/cities of Central Java Province

Only three regions (Semarang Regency, Kendal Regency, and Semarang City) show a significant negative relationship between poverty and EQI. The remaining 32 regions show no significant relationship.

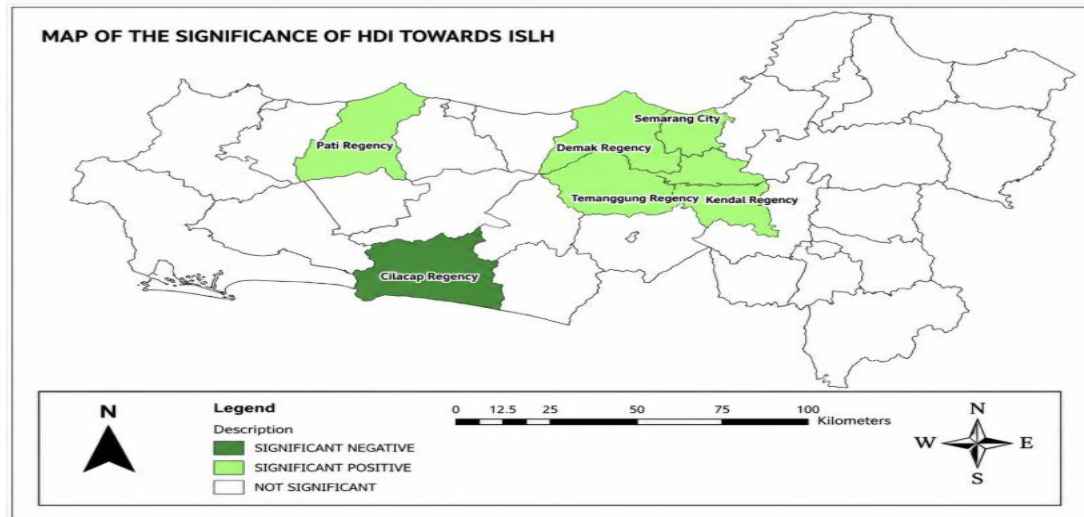


Figure 4. Significance of the effect of the Human Development Index (HDI) on the Environmental Quality Index (EQI) across 35 regencies/cities of Central Java Province

Kebumen Regency exhibits a significant positive relationship (green), while six regions (Semarang Regency, Temanggung Regency, Kendal Regency, Pemalang Regency, Salatiga City, and Semarang City) exhibit significant negative relationships (red). The other 28 regions are not significant.

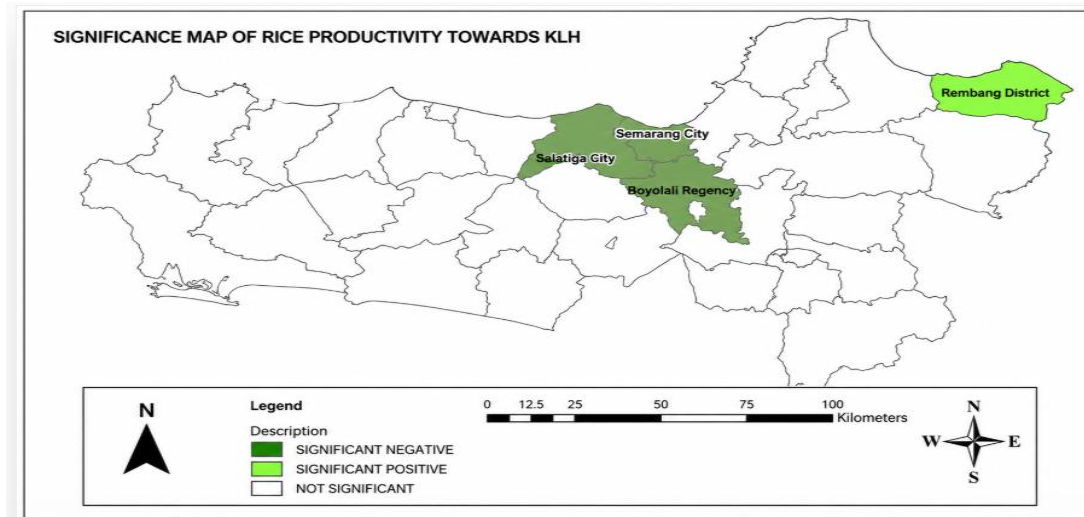


Figure 5. Significance of the effect of rice productivity on the Environmental Quality Index (EQI) across 35 regencies/cities of Central Java Province

Three regions (Semarang Regency, Kendal Regency, and Semarang City) show a significant positive relationship, one region (Rembang Regency) shows a significant negative relationship, and 31 regions show no significant relationship.

5. Discussion

The Effect of Poverty on the Environmental Quality Index in Regencies/Cities of Central Java Province

The Geographically Weighted Regression (GWR) results reveal that the influence of poverty on the Environmental Quality Index (EQI) is spatially uneven, with significant negative effects observed only in three regions: Semarang Regency, Kendal Regency, and Semarang City. The remaining 32 regencies and cities show no statistically significant relationship. This pattern confirms that poverty-driven environmental degradation is not universal but concentrated in specific urban–peri-urban environments where high population density, informal settlements, and resource extraction pressures are more pronounced.

The significant negative relationship in the three regions aligns with the theoretical thesis that poverty contributes to environmental degradation due to limited access to sustainable technology, clean energy, and proper sanitation (Nurjanana et al., 2025). In these areas, declining poverty rates have been accompanied by improvements in environmental programs such as air quality management, industrial waste treatment, water quality monitoring, and reforestation. This suggests that poverty alleviation, when combined with targeted environmental policy interventions, can generate a synergistic effect in improving regional environmental quality. These findings support the Environmental Kuznets Curve (EKC) hypothesis, which posits that as income rises and poverty declines, societies gain greater capacity to invest in environmental protection (Kumar et al., 2025; Polat & Çil, 2025).

However, the insignificance of poverty in the vast majority of regions challenges the traditional poverty–environment thesis, which assumes a universally negative relationship. In many districts, relatively higher poverty rates coexist with moderate or stable environmental quality. This outcome reflects how effective local governance, community initiatives, and geographical advantages can offset the adverse impact of poverty. Programs such as waste-to-fuel conversion, Climate Village campaigns, plastic recycling education, and cross-sector climate collaborations demonstrate that proactive policies can sustain environmental quality despite economic constraints. Furthermore, regions with abundant natural resources or preserved green areas may inherently possess greater environmental resilience.

The spatial heterogeneity found through GWR reveals that conventional global regression models would have oversimplified the relationship. Poverty triggers environmental pressure primarily when combined with rapid urbanization, industrial activity, and weak enforcement. The findings extend the theoretical understanding of the poverty–environment nexus in developing regions by demonstrating that the relationship is spatially conditional rather than universal. This implies that uniform poverty–environment strategies are inadequate; instead, region-specific approaches tailored to local socio-economic and ecological contexts are necessary.

The Effect of the Human Development Index on the Environmental Quality Index in Regencies/Cities of Central Java Province

The GWR results for the Human Development Index (HDI) reveal a mixed pattern, with only seven regions showing significant relationships: one region (Kebumen Regency) exhibits a significant positive effect, while six regions (Semarang Regency, Temanggung Regency, Kendal Regency, Pemalang Regency, Salatiga City, and Semarang City) show significant negative effects. The remaining 28 regions demonstrate no statistically significant association. This mixed pattern reflects the theoretical debate within Human Development Theory.

The positive relationship observed in Kebumen Regency supports the thesis that higher HDI reflecting improvements in education, health, and income enhances environmental awareness, encourages sustainable practices, and strengthens community engagement in ecological protection. In this region, human development improvements have been directed

toward environmental literacy, community-based programs, and integrated natural resource management. This finding aligns with studies by Ferraz et al. (2025) and Luo et al. (2025), which emphasize that human development should be measured not only by economic growth but also by the expansion of individual capabilities, including access to a healthy environment.

Conversely, the negative effects observed in the six urbanizing and industrializing regions support the antithesis perspective: rising HDI can worsen environmental quality through increased consumption, urban expansion, energy use, and industrial pressure. Despite relatively high HDI scores in these areas, environmental conditions face serious challenges, including air pollution, industrial waste contaminating water sources, and poorly managed land cover. This suggests that rapid human development has not been accompanied by sustainable environmental management, resulting in an imbalance between higher HDI and stagnating or declining environmental quality. These results are consistent with Polat & Çil (2025), who found that population density and HDI can exert a negative influence on environmental quality due to urbanization and industrialization pressures.

The findings demonstrate that HDI operates within a dual theoretical pathway. It can enhance environmental protection when governance capacity and environmental literacy are strong, as seen in Kebumen. Alternatively, it can worsen environmental conditions when economic development accelerates faster than environmental regulation, as observed in the six urban regions. The insignificance of HDI in the majority of regions further indicates that the relationship cannot be explained by human development levels alone. Factors such as effective environmental management policies, public awareness, and local socio-ecological conditions play decisive roles. For instance, some regions with high HDI still experience moderate environmental quality due to specific constraints such as low land cover quality or water pollution, indicating that HDI improvements have not yet translated into comprehensive environmental gains.

The Effect of Rice Productivity on the Environmental Quality Index in Regencies/Cities of Central Java Province

The GWR results for rice productivity show significant effects in only four regions. Three regions (Semarang Regency, Semarang City, and Kendal Regency) exhibit significant positive relationships, while one region (Rembang Regency) shows a significant negative relationship. The remaining 31 regions demonstrate no statistically significant influence. This indicates that the link between agricultural productivity and environmental quality is highly context-dependent, varying across regional characteristics and policy implementation.

The positive effects observed in the three regions align with the concept of sustainable intensification. In these areas, higher rice productivity has been achieved alongside environmental preservation through better land management, efficient use of inputs, and sustainable agricultural policies. Examples include regional regulations on sustainable food agricultural land protection, integrated and planned agricultural management programs, technological innovation, and sustainable resource use. These findings support the view that agricultural productivity can contribute positively to environmental quality when coupled with environmentally sound practices such as reduced chemical use, efficient irrigation, and circular economy principles (Manta et al., 2024; Mendonça et al., 2025).

In contrast, the negative effect observed in Rembang Regency supports the traditional Agricultural Intensification Theory, which argues that productivity gains often rely on heavy use of chemical fertilizers and pesticides, leading to soil degradation and water pollution. In this region, rising agricultural output has occurred without sustainable management practices, demonstrating that input-intensive farming can exacerbate environmental decline. This aligns with studies by Jauhari et al. (2025) and Wang et al. (2025), who found that intensive rice cultivation contributes to ecological degradation in developing regions.

The majority of regions show no significant relationship between rice productivity and EQI. This is often because agriculture is not the dominant sector influencing environmental quality. In many coastal or industrial regions, the industrial and manufacturing sectors contribute the largest share to the regional economy. These industries such as furniture and woodcraft production are resource-intensive and generate significant environmental pressures, including air emissions and waste affecting soil and water quality. Consequently, the moderate contribution of agriculture does not significantly alter the overall environmental quality. This finding implies the need for more integrated policies that balance agricultural development with industrial growth while ensuring environmental sustainability.

Spatial Grouping and Evidence for Spatial Heterogeneity

The grouping of significant variables across regencies and cities illustrates clear spatial heterogeneity, reinforcing the assumption of spatial econometric theory and supporting the hypothesis that the effects of poverty, HDI, and rice productivity differ geographically. Each variable forms distinct spatial clusters: poverty is significant primarily in urban–peri-urban clusters; HDI is significant in regions experiencing governance fragmentation or rapid urbanization; and rice productivity is significant in areas undergoing agricultural modernization or, conversely, maintaining traditional input-intensive farming systems.

Compared to previous studies that rely on global regression models, this research extends existing findings by demonstrating that ignoring spatial heterogeneity leads to oversimplified conclusions. The significant variability revealed by GWR strengthens the argument that environmental outcomes are shaped by multi-dimensional and location-specific interactions between socio-economic factors, human development patterns, and agricultural systems interactions, often invisible in national-level or non-spatial analyses.

The analysis also identifies several regions where none of the studied variables are significant. This suggests the presence of additional drivers of environmental quality, such as industrial emissions, land-use change, governance quality, and coastal ecological pressures. These areas represent important opportunities for future research to explore additional determinants beyond poverty, HDI, and agriculture.

Overall, the findings underscore the importance of adopting region-specific environmental policies that integrate poverty reduction, human development, and sustainable agricultural practices. Poverty alleviation should be combined with environmental protection in a synergistic manner. Human development strategies need to be directed toward aspects that encourage environmental awareness and responsible behavior. Finally, harmonization between the agricultural and industrial sectors through sustainable farming practices and green industry strengthening is essential to create a balance between economic development and environmental preservation across all districts and cities in Central Java.

6. Conclusion

The effect of poverty on the Environmental Quality Index (EQI) in Regencies/Cities of Central Java Province in 2023 has a significant influence. There are three regions, namely, Semarang Regency, Kendal Regency, and Semarang City have a significant negative relationship, while the other 32 regions do not show a significant influence between poverty and environmental quality. The effect of the Human Development Index (HDI) on the Environmental Quality Index (IKLH) in the Regencies/Cities of Central Java Province varies. A total of seven regions showed significant relationships, namely Kebumen Regency had a positive relationship, and six Regencies/Cities showed negative relationships (Semarang Regency, Temanggung Regency, Kendal Regency, Kendal Regency, Pemalang, Salatiga City, and Semarang City). In addition, the other 28 districts/cities did not show a significant relationship. Rice productivity to

the Environmental Quality Index (EQI) in the Regency/City of Central Java Province varies. There are four regions, namely Semarang Regency, Semarang City, and Kendal Regency, showing a positive relationship, while Rembang Regency shows a negative relationship. However, the majority of regions (31 districts/cities) did not show a significant influence.

Based on the results of the research, it is recommended that local governments in Central Java Province integrate poverty alleviation policies with environmental protection in a sustainable manner. Furthermore, increasing the Human Development Index (HDI) needs to be directed at aspects that encourage awareness and environmentally friendly behavior. Finally, there is a need for harmonization between the agricultural and industrial sectors through the implementation of sustainable agricultural practices and the strengthening of green industries in order to create a balance between economic development and overall environmental preservation in all districts/cities in Central Java

7. Implication of research

This study offers both theoretical and practical contributions. Theoretically, it advances spatial econometrics by applying Geographically Weighted Regression (GWR) to subnational environmental quality, supporting and extending the Environmental Kuznets Curve (EKC) hypothesis in developing countries. Empirically, it highlights how poverty, human development, and agricultural productivity interact to affect environmental outcomes. Practically, the findings guide policymakers in prioritizing environmental interventions in districts most affected by poverty or intensive agriculture, promoting synergy between environmental protection and poverty alleviation. Strengthening human development strategies through environmental literacy and green infrastructure, alongside encouraging sustainable agricultural practices, is emphasized. Globally, this research underscores the importance of subnational, data-driven spatial analysis for inclusive green growth and location-specific environmental governance.

8. Limitation of study and future research

This study has several limitations that need to be considered and can be used as material for further research. One of the limitations is the use of cross-sectional data from 2023, so this study is not yet able to capture temporal dynamics or long-term trends in environmental quality. In addition, only three variables were used, namely poverty, Human Development Index (HDI), and rice productivity, while other important environmental factors, such as industrial emissions, land use change, or governance quality were not included due to data limitations.

Another limitation relates to the Environmental Quality Index (EQI) used as the dependent variable. The EQI is a composite index that covers several components, such as air, water, and soil quality, thus potentially obscuring specific environmental problems at the local level. In addition, the research focus, which was limited to Central Java Province, restricted the ability to generalize the results to other regions with different social and ecological contexts.

In the future, it is recommended that panel data be used so that spatial and temporal dynamics can be analyzed in greater depth and cause-and-effect relationships can be tested more rigorously. The addition of other explanatory variables such as industrial activity, waste management, urban expansion, and local environmental governance, will enrich the analysis model. A mixed-method approach that combines quantitative spatial models with qualitative field research can also help capture institutional, cultural, and behavioral dimensions in environmental management. Additionally, comparative studies between provinces or countries can provide broader insights into spatial environmental inequalities and support the development of more general policies for inclusive green development.

Authors' contributions and responsibilities

Herman Cahyo Diartho led the conceptual framework and study design, coordinated the overall research process, and contributed to the theoretical background, discussion, and critical revision of the manuscript for important intellectual content. Agus Luthfi developed the methodology, performed spatial econometric modeling using GWR (Geographically Weighted Regression), conducted the statistical analysis, and was responsible for data validation and interpretation of the results. Iddo Rifqy Nugraha carried out data collection and preparation, created visualizations and spatial maps, wrote the original draft of the manuscript, and handled formatting, references, and submission management. Nur Zaimah Ubaidillah contributed to manuscript review, interpretation of results, international academic refinement, and improvement of the discussion section, particularly in strengthening the sustainability and environmental policy perspectives.

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Competing interests

The authors declare that there are no competing interests, financial or non-financial, that could have influenced the research, authorship, or publication of this article. All research activities were conducted independently and free from any conflict of interest.

Data availability statement

Processed data and spatial analysis outputs are available from the corresponding author upon reasonable request.

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