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Spatial Analysis of the Driving Factors Behind Agricultural Land Conversion in Relation to Food Security Policy (Case Study: Bogor Regency)

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Abstract: The conversion of agricultural land to non-agricultural uses poses a significant threat to food security, particularly in metropolitan buffer regions such as Bogor Regency. Rapid population growth and economic restructuring have led to a 24.5% reduction in rice field area, declining from 48,177 ha in 2003 to 36,355 ha in 2019, contributing to a regional rice deficit of 37%. This study employs a quantitative spatial approach using Geographic Information Systems (GIS), integrating Spatial Overlay, Cellular Automata (CA), and a Multi-Layer Perceptron Artificial Neural Network (MLP-ANN) to analyze land conversion dynamics and evaluate the effectiveness of spatial planning policies. The results reveal persistent conversion of rice fields, including within designated food crop zones under the Regional Spatial Plan (RTRW), indicating a misalignment between spatial planning and actual land-use dynamics. This study contributes to applied environmental science by demonstrating the value of integrated spatial modeling in assessing land-use policy effectiveness and supporting spatially informed strategies for sustainable agricultural land management and local food security.

Keywords: Cellular automata; Food security; Land conversion; MLP-ANN; Spatial planning policy

Introduction

Food is a fundamental human need, and achieving food security has become a strategic issue for Indonesia, whose population is projected to reach 334 million by 2050 (Ayuningrum, 2023; Sumunar & Budiman, 2021). However, rapid population growth has not been accompanied by an increase in agricultural land availability, as farmland continues to be converted into residential and industrial areas (Pribadi & Pauleit, 2015; Liu et al., 2020; Viana et al., 2023; Dharyan et al., 2025). This trend has reduced food production capacity and increased national food vulnerability (Faoziyah et al., 2024).

Java Island experiences the highest rate of agricultural land conversion in Indonesia, averaging 8,346.65 ha per year (Wirapradeksa, 2024). Bogor Regency, located within the Jabodetabek metropolitan area, faces substantial pressure due to the highest population growth rate in West Java at 12.10 percent. As a result, paddy field area declined by 24.5 percent from 48,177 ha in 2003 to 36,355 ha in 2019, at an annual rate of –1.57 percent, contributing to a regional rice deficit of 37 percent in 2018. Population growth, migration dynamics, infrastructure development, economic structural change, and high land prices further accelerate agricultural land conversion (Ivanka R et al., 2024)

Although land-use control has been regulated through Law No. 26 of 2007 on Spatial Planning and implemented in the West Java Provincial Spatial Plan 2022–2042 (2022) and the Bogor Regency Spatial Plan (2016) conversion continues to occur even within designated agricultural zones due to weak policy implementation (Wibisono & Widowaty, 2023). This

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condition indicates a gap between spatial planning policies and actual land-use dynamics.

Addressing this gap, this study aims to: (1) analyze the relationship between population growth and agricultural land conversion in relation to food security dynamics, and (2) assess the influence of spatial planning policies on the sustainability of agricultural land. The novelty of this research lies in the integrated application of spatial overlay analysis, Cellular Automata, and a Multi-Layer Perceptron Artificial Neural Network (MLP-ANN) to identify driving factors of land conversion and evaluate their consistency with regional spatial plans (Hezbollah et al., 2025). This integrated approach contributes to applied environmental science by strengthening data-driven spatial modeling for sustainable land management and environmentally based science education.

Method

This study applied a quantitative spatial analysis to examine the driving factors of agricultural land conversion and its implications for food security and agricultural land sustainability (Murdaningsih et al., 2017). The study area covered Bogor Regency, using spatial and time-series data from 2016–2022 obtained from Statistics Indonesia (BPS), sectoral agencies, and regency and provincial spatial plans (RTRW). Spatial datasets included paddy fields, spatial planning patterns, road and river networks, industrial areas, residential areas, and public facilities, all converted into raster format with a 30 m spatial resolution.

Research Design

The research consisted of three stages: analysis of paddy field land-use changes in relation to population growth; modeling land conversion drivers using an integrated Multi-Layer Perceptron Artificial Neural Network (MLP-ANN) and Cellular Automata (CA); and evaluation of simulated land-use changes against regional spatial plans to assess policy effectiveness.

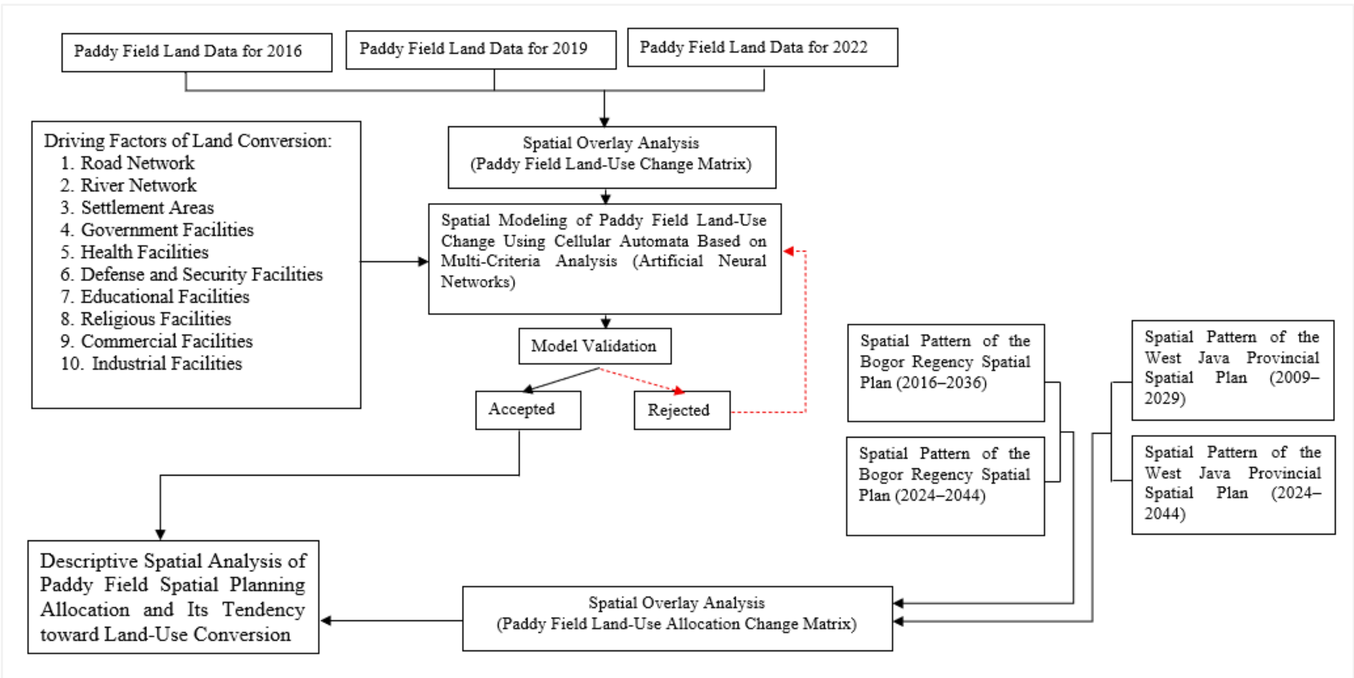

Figure 1. Methodological flowchart

Spatial Overlay Analysis

Spatial overlay analysis was used to identify paddy field changes in 2016, 2019, and 2022 and their relationship with residential and industrial expansion. The results were compared with the Bogor Regency Spatial Plans (Regional Regulation No. 11 of 2016 (2016) and the West Java Provincial Spatial Plan 2022–2042 (2022). to determine the extent and spatial distribution of land conversion.

MLP-ANN Modeling

MLP-ANN estimated transition probabilities of paddy fields converting to non-agricultural land based on 13 driving factors, including proximity to residential areas, road and river networks, public facilities, industrial zones, and built-up land dynamics (Rizqi & Manessa, 2025; Zahrayni et al., 2025). The model generated factor weights indicating the relative influence of each variable (Nugroho et al., 2025) and was selected for its ability to capture complex, non-linear relationships among heterogeneous spatial variables (Tsumita et al., 2025; Zhu et al., 2024; Castillo-Girones et al., 2025).

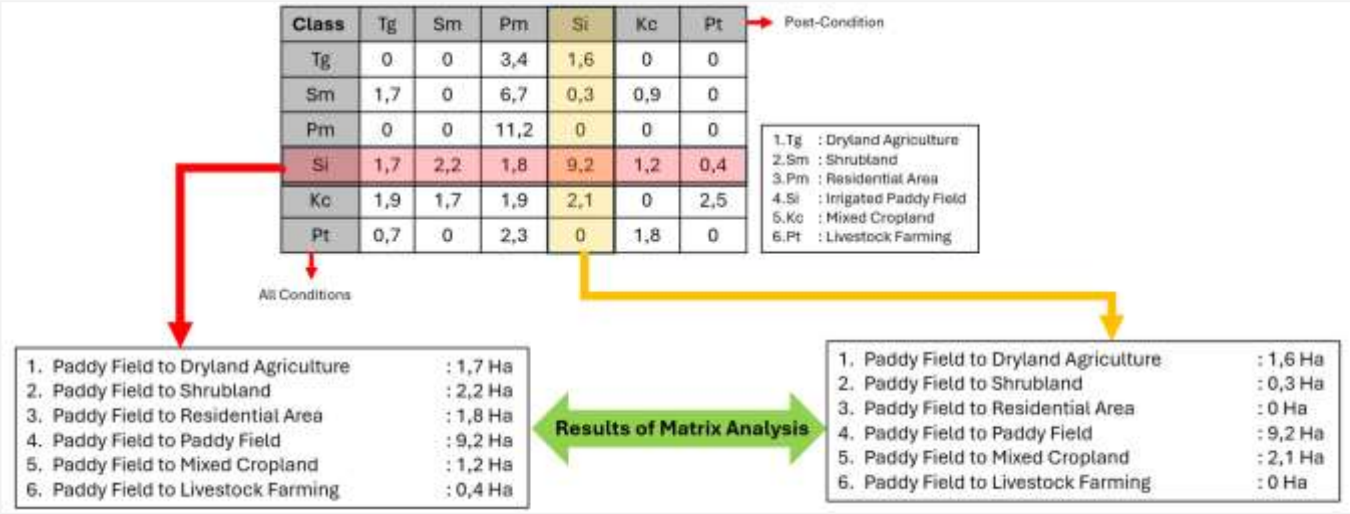

Figure 2. Spatial overlay matrix of land-use change

Cellular Automata Simulation and Validation

Cellular Automata simulation was conducted using the MOLUSCE plugin in QGIS to predict paddy field changes for 2025 and 2030, applying MLP-ANN transition probabilities and a Von Neumann neighborhood (Kartikasari et al., 2025). This simulation produced predictive maps of land conversion. Model performance was evaluated using Overall Accuracy and the Kappa Coefficient, which indicated substantial agreement between simulated and observed land-use patterns. Cross-validation and limited field verification were conducted in sub-districts with the highest conversion rates (Wilimitis & Walsh, 2023).

Outputs

The study produced spatial risk maps of paddy field conversion, identification of dominant driving factors, predicted land-use change maps for 2025 and 2030, and conformity assessments between existing and projected paddy fields and regional spatial plans. These outputs support spatially informed strategies for agricultural land protection and food security policy.

Results and Discussion

This section presents the results of spatial and quantitative analyses of land-use change in Bogor Regency, focusing on paddy field conversion dynamics, the effectiveness of spatial planning policies, and implications for regional food security.

Population Growth and Pressure on Agricultural Land

Population growth in Bogor Regency has continuously increased, intensifying demand for space for settlements and infrastructure. This trend aligns with global patterns in which population growth directly accelerates agricultural land conversion (World Population Prospects 2019 Highlights, 2019). Areas in northern Bogor Regency with high accessibility have experienced the greatest development pressure.

Changes in agricultural land are evident from the decline in paddy field area over time.

Table 1. Changes in Paddy Field Area in Bogor Regency (2016–2022)

Year	Area (Ha)	Description
2016	47.098,8	Spatial model input
2019	46.150,0	Spatial model input
2022	41.988,2	Model validation

The data indicate a decrease of 10.8% in paddy field area over the study period. Overlay analysis identifies 2019–2022 as the most critical phase of conversion, with a loss of 4,161.8 ha. Spatially, this conversion is strongly correlated with proximity to road networks and public service facilities, confirming accessibility as a dominant driver of paddy field conversion.

Effectiveness of Spatial Planning Policies in Preserving Paddy Fields

Spatial planning policies are intended to regulate land use and protect agricultural land. However, comparison between the Bogor Regency Spatial Plan (RTRW) 2016–2036 and the revised RTRW 2024–2044 shows a reduction in designated agricultural areas from 39,435.4 ha to 37,706.1 ha. This change reflects increasing accommodation of built-up land expansion within spatial planning frameworks.

Spatial analysis further indicates that paddy field conversion is influenced not only by zoning designation but also by uneven interregional development pressure.

As illustrated in Figure 3, the highest conversion during 2016–2022 occurred in Jasinga District (364.2 ha), followed by Sukamakmur, Parung Panjang, Ciseeng, and Gunungputri, demonstrating a spatially clustered conversion pattern.

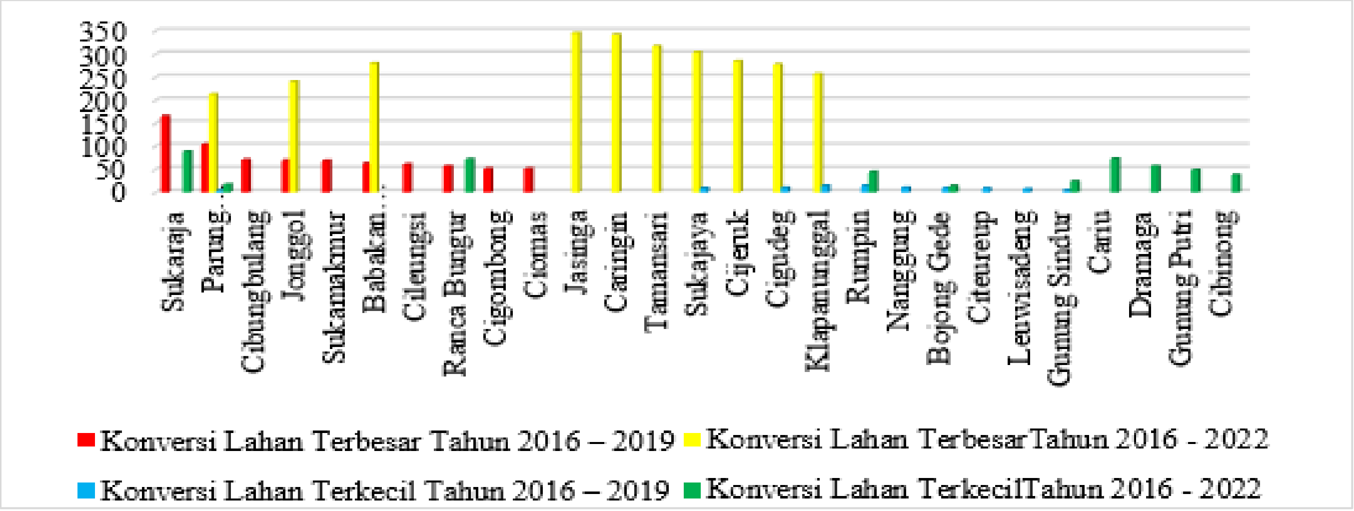

Figure 3. Conversion of rice paddy land to non-paddy uses in Bogor Regency

Interpretation of MLP-ANN and CA Model Results

Table 2. Projected Paddy Field Conversion (2022–2034) Based on the Bogor Regency Spatial Plan (2024)

Spatial Designation	Area Converted (Ha)
Water bodies	71.1
National park	233.6
Protected forest	72.7
Unique landscape area	0.1
Limited production forest	190.4
Local protection area	9.3
Defense and security area	2.4
Mining area	4.6
Livestock protection area	9.8
Nature tourism park	2.0
Urban settlement/tourism area	0.3
Aquaculture area	311.8
Plantation area	467.6
Food crop cultivation area	2,681.9
Horticultural area	396.3
Rural settlement area	467.6
Urban settlement area	1.894.9
Industrial area	99.5
Tourism area	106.0
Total	7,151.4

Simulation results using the MLP-ANN and Cellular Automata (CA) models project an additional paddy field loss of 7,151.4 ha by 2034. Districts such as Sukamakmur, Nanggung, Pamijahan, Jonggol, and Leuwiliang are projected to experience the highest conversion rates. From a scientific perspective, this pattern indicates a path-dependency effect, where areas with historical conversion tendencies remain persistent hotspots due to the accumulation of spatial driving factors.

The overlay between projected land-use change and the Bogor Regency RTRW 2024 is summarized in Table 2. The results show that the largest projected conversion occurs within food crop cultivation zones, indicating that even areas formally designated for agriculture remain highly vulnerable. Scientifically, this highlights the limited capability of static zoning regulations to counteract dynamic spatial drivers captured by the MLP-ANN and CA models.

Impacts of Paddy Field Conversion on Food Security

Rice production serves as a key indicator of food security in Bogor Regency. As shown in Table 3, declining paddy field area has directly reduced rice production.

Table 3. Paddy Field Area and Rice Production in Bogor Regency (2016–2022)

Year	Paddy Field Area (Ha)	Rice Production (Tons)
2016	47,098.8	492,207.00
2019	46,150.0	307,860.90
2022	41,988.2	299,893.80

Rice availability and demand in 2022 are presented in Table 4. Based on these data, rice demand in 2022 reached 507,061.47 tons/year, resulting in a deficit of 181,123 tons/year. Future projections for 2034 are presented in Table 5.

Table 4. Rice Availability and Demand in Bogor Regency (2022)

Paddy Field Area	Paddy Production (Tons/Year)	Rice Production (Tons/Year)	Population (Persons)	Rice consumption
41,988.2 Ha	299,893.80	325,938	5,556,838	250 g/person/day

Table 5. Projected Rice Production and Demand in Bogor Regency (2034)

Paddy Field Area	Paddy Production	Rice Production	Projected Population	Rice Demand
38,972.4 Ha	214,348.2 Tons/Year	128,608.92 Tons/Year	6,542.460 Persons	596,999,5 Tons/Year

The projected rice deficit in 2034 is estimated at 468,390 tons/year, nearly three times higher than in 2022. This finding demonstrates that continued paddy field conversion significantly weakens regional food security and increases dependence on external food supplies. Scientifically, it underscores the critical link between spatial land-use dynamics and long-term food system sustainability.

Conclusion

This study demonstrates that agricultural land conversion in Bogor Regency is a persistent process driven by the interaction of demographic pressure, spatial accessibility, and weak spatial planning enforcement. High population growth, particularly in highly accessible areas, accelerates the conversion of irrigated paddy fields into residential and built-up land, with strong spatial associations with road networks, public facilities, and economic centers. The integrated MLP–ANN and Cellular Automata modeling indicates that land conversion occurs not only within designated development zones but also within agricultural and limited protected areas, with a projected additional loss of 7,151.4 ha of paddy fields by 2034. This trend substantially reduces regional rice production capacity, resulting in a current rice deficit of 181,123 tons per year and a projected deficit of 468,390 tons per year by 2034. Overall, the findings highlight that the sustainability of agricultural land and food security in Bogor Regency are increasingly threatened, underscoring the urgent need for stronger protection of strategic agricultural land, improved spatial planning compliance, and better alignment between planning policies and actual land-use dynamics.

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Author Contributions

Conceptualization, R.P.D. and P.; methodology, R.P.D.; software, R.P.D.; validation, R.P.D., P., and L.A.; formal analysis, R.P.D.; investigation, R.P.D.; resources, R.P.D.; data curation, R.P.D.; writing—original draft, R.P.D.; writing—review & editing, P. and L.A.; visualization, R.P.D.; supervision, P. and L.A.; project administration, R.P.D.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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