FORUM GEOGRAFI
ISSN: 0852-0682 | E-ISSN: 2460-3945
HTTPS://JOURNALS.UMS.AC.ID/INDEX.PHP/FG/

Research article

Balancing Urban Growth and Food Autonomy: An Integrated Machine Learning and Agricultural Statistics Framework for Local Rice Self Sufficiency in the PNAR of Purwokerto, Indonesia

Bayu Rizqi*, Masita Dwi Mandini Manessa

Department of Geography, Faculty of Mathematics and Natural Sciences, University of Indonesia, Jl. Lingkar Pondok Cina, Depok 16424, Indonesia

*) Correspondence: bayu.rizqi@ui.ac.id

Citation:
Rizqi, B., & Manessa, M. D. M. (2025). Balancing Urban Growth and Food Autonomy: Scenario-Based Modeling of Local Rice Self-Sufficiency in the PNAR of Purwokerto, Indonesia. Forum Geografi. 39(3), 420-437.

Article history:
Received: 18 July 2025
Revised: 14 October 2025
Accepted: 21 November 2025
Published: 11 December 2025

Abstract

Rapid peri-urbanization intensifies competition between settlement growth and farmland, creating structural risks to local food security. This study integrates machine learning–based spatial modeling, agricultural statistics, and policy-relevant scenarios to examine how land use trajectories influence local rice self-sufficiency in the Proposed New Autonomous Region (PNAR) of Purwokerto, Indonesia. Multi-temporal Sentinel-2 imagery served as input for Random Forest–based classification of existing land use, whereas CA–ANN was used to simulate transitions and predict land use in 2029. The Random Forest classification model achieved an overall accuracy of 84% with a Kappa coefficient of 0.81, while CA–ANN model validation through hindcasting for 2015–2024 reached 82% spatial agreement, with strong class stability for paddy fields (0.853) and built-up areas (0.973). Under the business-as-usual path, paddy fields decline from 8,506 ha (2015) to 6,512 ha (2029), shifting the rice balance from a +3,791 tons surplus to a –12,520 tons deficit. A combined scenario cropping index of 250, a 2% conversion reduction, and 4% population moderation restores near-equilibrium (+190 tons). These findings confirm that safeguarding peri-urban food resilience requires coordinated land use regulation, demographic control, and agrotechnological intensification. The validated CA–ANN framework offers a transferable decision-support tool for sustainable land-food governance in rapidly growing regions of the Global South.

Keywords: paddy field conversion; rice self-sufficiency; random forest classification; CA–ANN simulation; machine learning.

1. Introduction

Food security has remained a major global agenda since the World Food Conference in 1974; however, hunger persists as a critical challenge worldwide (Ahmed & Turchini, 2021; Jiang *et al.,* 2021). Currently, one in ten people worldwide still suffers from hunger, particularly in regions with high poverty rates (Owubah, 2024). As the primary source of carbohydrates for more than half of the world's population, rice plays a central role in the global food system, contributing nearly 60% of total caloric intake, with paddy fields serving as its main production base (FAO, 1995). Yet rapid population growth and shifting land use values have triggered extensive conversion of paddy fields into urban areas, resulting in the loss of approximately 5–7 millions hectares of agricultural land each year (Ahmed & Turchini, 2021). Paddy fields are the most vulnerable targets of conversion because they are typically located on flat terrain, close to residential zones, and often carry relatively low economic valuation (Fahri *et al.,* 2014). These global tendencies reveal that food security is determined not only by production capacity but also by the spatial configuration and sustainability of agricultural landscapes.

Despite its agrarian identity, Indonesia faces a persistent paradox in food security. Rice is consumed by more than 90% of the population (Siregar, 2018), remains the main staple, yet the country has rarely achieved self-sufficiency since the early 2000s. The average import volume reaches 1.1 million tons annually, peaking at 4.5 millions tons in 2024, the highest in the last seven years (Patunru & Ilman *et al.,* 2019; Dawe, 2008; Saleh *et al.,* 2025; Statistic Indonesia, 2025). Dependence on imports from Thailand, Vietnam, and India (Destiarni *et al.,* 2024) exposes Indonesia's structural vulnerability to international market fluctuations and policy shocks.

Meanwhile, rapid urbanization exacerbates food insecurity through the large-scale conversion of agricultural land. Indonesia ranks among the countries with the fastest paddy field loss in the world, averaging 78,184 hectares per year during 1990–2000, with Java Island bearing a conversion rate four times higher than other regions (Purbiyanti *et al.,* 2017; Wahyunto & Widiastuti, 2014). The loss of productive irrigated fields under urban pressure has reduced national rice output and weakened self-sufficiency. This phenomenon is particularly evident in Banyumas Regency. This regency is part of the Cibalingmas (Cilacap–Banyumas–Purbalingga) Growth Corridor, according to the Central Java Spatial Plan Regulation No. 8 of 2024, where Purwokerto functions as the Regional Activity Center, driving economic connectivity. This strategic position places

Banyumas as a balancing axis between the southern coastal region and the agrarian hinterland of Central Java, as well as an important component of the Sustainable Food Agricultural Land (LP2B) network that supports regional food security. However, rapid urban growth, particularly in Purwokerto, poses increasing threats to agricultural land. Between 2007 and 2019, the regency lost 1,231 hectares (3.87%) of paddy fields, mostly in Purwokerto and its surrounding peri-urban zones (Munibah *et al.,* 2024), and projections indicate a further decline of 1,383.8 ha by 2045, reducing total paddy land to 29,159.6 ha.

This condition illustrates the paradox of regional development, in which Banyumas is simultaneously expected to accelerate economic growth while preserving agrarian and ecological sustainability. The complexity has intensified with the proposed establishment of the New Autonomous Region (PNAR) of Purwokerto, encompassing four urban subdistricts (Purwokerto Timur, Utara, Barat, and Selatan) and five peri-urban buffers (Sumbang, Kembaran, Baturraden, Kedungbanteng, and Karanglewas). As a mixed urban–agrarian territory, the proposed PNAR has already experienced rapid land use intensification for housing, infrastructure, and economic activities. Land conversion has accelerated even before administrative expansion occurs. Increasing demand for urban space has driven the transformation of productive paddy fields into residential areas and commercial zones. Data indicate that paddy production in the PNAR subdistricts declined from 96,941 tons in 2019 to 80,149 tons in 2024, a reduction of approximately 17% (Banyumas Communication and Informatics Department, 2025).This trend confirms that urban pressure on agricultural land is progressive, and once regional expansion is formalized, conversion intensity will likely rise further due to investment inflows, infrastructure expansion, and rising land values (Etim *et al.,* 2024). Thus, Purwokerto's urban growth represents not only physical expansion but also profound implications for local agrarian systems and regional food sustainability.

Existing research on this issue remains fragmented. Spatial–predictive studies have explored urban expansion and land use dynamics, but those that link them with regional rice balance or food supply vulnerability are limited (Alikhanov *et al.,* 2024; Audina *et al.,* 2019; Ayalew & Nigussie, 2023; Gilbert & Shi, 2024; Manjarrez-Domínguez *et al.,* 2023; Molla *et al.,* 2024). Conversely, economic or sectoral analyses of rice self-sufficiency emphasize production–consumption equilibrium while neglecting spatial drivers (Oort *et al.,* 2015; Siti Syamsiar, 2013; Susanto & Suhono, 2019). Meanwhile, governance-oriented research tends to remain normative and lacks empirical coupling between land transformation and food system performance (Setiadi *et al.,* 2021; Setiartiti, 2021; Siregar, 2018). This reveals a key research gap: the absence of an integrated framework that links the spatial dynamics of paddy-field conversion to agricultural statistics to assess local food supply vulnerability. Existing studies remain fragmented, focusing either on GIS-based land use modeling or on statistical food-balance analysis, and rarely integrate both into a cohesive, evidence-based framework. Moreover, despite its strength in capturing spatial transformations, remote sensing has often been underutilized or insufficiently integrated with food system analytics. Therefore, an integrated modeling approach combining GIS, remote sensing, and agricultural statistics is needed to better capture land transformation and its implications for rice availability. By coupling land use projections with rice-availability scenarios, a more comprehensive understanding of regional carrying capacity and food security risks can be achieved, thereby supporting spatially informed and targeted policy interventions.

This study addresses the spatial–aspatial dimensions of food security by investigating how the conversion of paddy fields affects rice production and regional self-sufficiency in the PNAR of Purwokerto. Specifically, it (1) analyzes the spatial pattern of paddy-field conversion from 2015 to 2024 and projects land use changes to 2029 using integrated remote sensing and CA–ANN modeling; (2) estimates current and projected rice balances based on production and consumption trends; and (3) evaluates rice self-sufficiency levels to formulate scenario-based strategies for sustainable food policy. The findings are expected to provide scientific input for spatial planning and food security governance, particularly in refining regional spatial plans (RTRW) to prioritize paddy-field protection and strengthen food system resilience. Beyond its national significance for agrarian modernization and import reduction, the integrated modeling framework developed in this research offers a transferable approach for other peri-urban regions in the Global South facing similar land use transitions and food supply vulnerabilities. By bridging spatial transformation analysis with agricultural balance modeling, this study advances a more comprehensive understanding of how urban growth reshapes regional food autonomy and contributes to evidence-based spatial policy for sustainable land management.

2. Research Methods

This study employed a quantitative design with a mixed-methods approach, integrating both exploratory and descriptive components to combine spatial and aspatial data within a holistic analytical framework. Geospatial data provided visual and predictive insights into land conversion dynamics, while statistical data were utilized to calculate the rice balance and formulate policy recommendations. The exploratory aspect of the study involved identifying spatial patterns of paddy field conversion in the PNAR of Purwokerto using geospatial data, which were validated through field accuracy assessments. The descriptive approach was applied to analyze the impact of paddy field conversion on rice production and availability, drawing on statistical data such as rice production volumes, population figures, and per capita rice consumption to project future consumption needs up to 2029. This combination allowed the research to explain phenomena, explore intervariable relationships, and provide a strategic basis for planning rice self-sufficiency amidst increasing urbanization pressure. Although the spatial plan of Banyumas Regency extends to 2045, 2029 was selected as the projection target because it marks the end of the first medium-term development phase (2025–2029). If rice self-sufficiency is achieved at this stage, the focus for the remainder of the period until 2045 can shift to maintaining the achieved balance.

Satellite imagery analysis employed Sentinel-2 Level-2A Surface Reflectance data retrieved from the Google Earth Engine (GEE) platform covering the period January 2024 to February 2025, filtered to a maximum cloud-cover threshold of 20 percent. The preprocessing stage included cloud masking using the MSK_CLDPRB band with a 30% probability threshold, followed by morphological dilation–erosion filtering to remove residual cloud and shadow artifacts. A median composite was subsequently generated to produce a spectrally stable and seasonally balanced mosaic for further analysis. To enhance visual separability among land use classes, Sentinel-2 Level-1C natural-color composites (Bands 4–3–2, 10 m) were employed during classification. This combination leverages the radiometric accuracy of Level-2A for preprocessing and the visual clarity of Level-1C in the visible spectrum, where the red band (B4) discriminates impervious and bare-soil features, the green band (B3) captures chlorophyll reflectance from vegetated areas, and the blue band (B2) accentuates flooded or water-saturated paddy plots. Multi-temporal composites from 2015 and 2019 were also incorporated as baseline and calibration references, representing the pre-expansion and mid-transition phases of Purwokerto's urbanization, thereby ensuring consistent temporal comparability and reliable land use validation up to 2024.

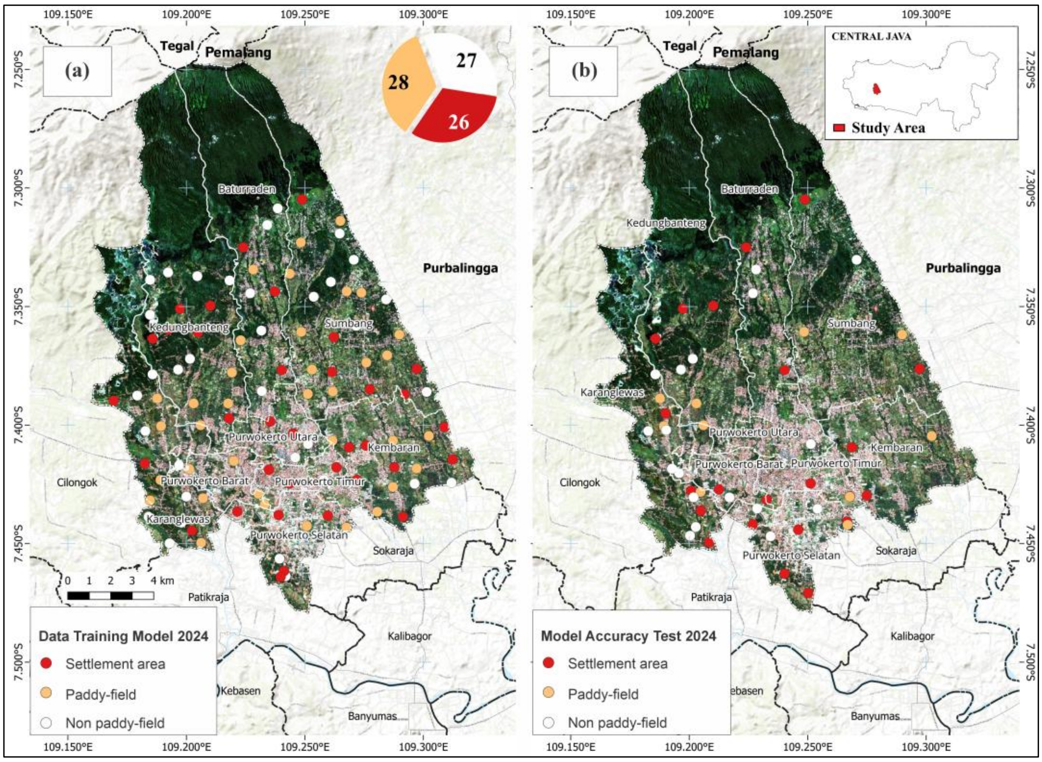

Figure 1. Map of Training Data (a) and Accuracy Test Points (b) for the 2024 Land use Classification.

Land use classification for 2024 was conducted using the Random Forest (RF) algorithm via QGIS's Semi-Automatic Classification Plugin, distinguishing three classes: settlement, paddy field, and non–paddy field. RF was selected for its proven robustness, with accuracy improvements up to 10% over traditional classifiers (Valero Medina & Alzate Atehortúa, 2019). The RF model was trained with 81 ground-truth samples (28 paddy fields, 26 settlements, 27 non-paddy vegetation) obtained from field surveys and high-resolution imagery. Configured with 120 decision trees, a minimum split size of 2, and a feature limit of √p (max = 2), the classifier balanced model complexity and generalization, supported by One-vs-Rest multiclass discrimination and cross-validation for internal reliability. Class weights were kept equal, given the balanced sample distribution, while five iterative estimator refinements optimized prediction stability. Model performance was evaluated using 50 independent ground truth points through a confusion matrix to measure accuracy (Figure 1.b), supplemented by a transition matrix analysis in both probability and area-based (hectare) formats to assess robustness.

Future projection for 2029 employed the Cellular Automata–Artificial Neural Network (CA–ANN) model within QGIS's MOLUSCE plugin, widely applied for simulating non-linear land use dynamics (Baig *et al.,* 2022; Entahabu *et al.,* 2023; Kou *et al.,* 2023; Uddin *et al.,* 2023; Arfasa *et al.,* 2023; and Kayitesi *et al.,* 2024). The model used a Multi-Layer Perceptron (MLP) with one hidden layer of five neurons to capture complex interactions among five spatial driving factors: slope, road proximity, population density, and distances to district and subdistrict centers, optimized with a learning rate of 0.1, momentum 0.02, and 800 iterations for stable convergence. A 1-pixel (10 m) neighborhood preserved local spatial heterogeneity, avoiding excessive smoothing in mixed urban–agricultural mosaics. Calibration used observed transitions from 2015–2019 (RF-derived) to produce transition potential surfaces that reflect spatial relationships between land use change and driving factors. Validation via hindcasting (2019–2024) achieved overall accuracy of 87.54% and a Kappa of 0.803 (histogram: 0.957; location: 0.839), confirming strong alignment between simulated and observed distributions. This validated model was retained for the 2029 Business-as-Usual projection, using 2019–2024 transition patterns to capture current conversion trends and the 2024 map as the initial state, combining temporal robustness with spatial realism to simulate Purwokerto's ongoing urban–agricultural transformation.

The CA–ANN model incorporated five spatial driving factors: slope, proximity to roads, population density, and distances to district and subdistrict centers (Table 1). All aspects were processed as 10 × 10 m raster layers consistent with Sentinel-2 resolution and classified into three suitability levels (1–3). Slope was derived from DEMNAS (0.27 arc-second) and categorized into 0–3%, 3–15%, and >15%, while proximity to roads was mapped using 100 m buffers from RBI 1:25,000 (2022). Population density, ranging from 54,204 (Purwokerto Utara) to 105,678 (Sumbang) inhabitants, was modeled using subdistrict-level BPS data (2015–2024) projected to 2029, with settlement centroids interpolated through Kernel Density Estimation (KDE) to produce a continuous surface of demographic intensity subsequently reclassified into low, medium, and high human pressure zones. Distances to district and subdistrict centers were delineated through 5 km and 2 km buffers, respectively, based on digitized administrative points. Each factor was weighted according to its influence on land use change: road proximity (30%) and population density (20%) being the most dominant, followed by slope (20%), distance to district centers (15%), and distance to subdistrict centers (15%) reflecting that areas with flat terrain, dense populations, and high accessibility are the most vulnerable to paddy-field conversion (Munibah et al., 2024).

Table 1. Weighting and Scoring of Driving Factors for Land Use Change Prediction.

No	Variable	Class	Priority Score	Conversion Susceptibility	Weight	Role in Model
1.	Slope (% percent)	0-3%	3	Significant	20%	Represents a topographic constraint; gentle slopes favor settlement expansion
		3-15%	2	moderately significant		
		>15%	1	no significant		
2.	Roads proximity (meters)	0-100 m	3	Significant	30%	Accessibility driver; proximity to roads increases conversion likelihood
		100-200 m	2	moderately significant		
		>200 m	1	no significant		
3.	Population density interpolation (KDE index)	High	3	Significant	20%	Socio-demographic pressure indicator driving built-up expansion
		Medium	2	moderately significant		
		Low	1	no significant		
4.	Distance to regional centers (meters)	0-5 km	3	Significant	15%	Captures regional centrality and economic gravity
		5-10 km	2	moderately significant		
		>10 km	1	no significant		
5.	Distance to subdistrict centers (meters)	0-2 km	3	Significant	15%	Represents local-scale service accessibility
		2-4 km	2	moderately significant		
		>4 km	1	no significant		

source: Modified from Pratami *et al.,* (2019), Sugandhi *et al.,* (2022), Rizqi & Manessa, (2025) By the authors, 2025.

The rice availability balance was calculated by comparing the estimated rice supply with the projected domestic demand. Supply was determined by multiplying the harvested rice yield by a standard conversion coefficient of 51.24% by Statistics Indonesia (BPS), which reflects the average percentage of harvested paddy that becomes consumable rice after post-harvest processing, drying, and milling. Demand was estimated by multiplying the total population by the net per capita rice consumption rate for 2024 (79.08 kg capita^{-1} year^{-1}), as reported by the National Food Agency (Bapanas), and assuming this value remained constant across the analyzed time series to ensure consistency in demand estimation. The projected rice production for 2029 was estimated by multiplying the average land productivity in base years 2015, 2019, and 2024 by the modeled paddy field area from the CA-ANN simulation. Meanwhile, projected rice demand for 2029 was derived by multiplying population projections by per capita rice consumption. These calculations formed the basis for evaluating rice surplus or deficit for the years 2015, 2019, and 2024, as well as for the 2029 projection. The study also generated policy recommendations based on three scenario models, Business as Usual (BaU), Moderate, and Optimistic, to assess the effects of various combinations of factors, including cropping index (CI), population growth rate, and paddy field conversion, on the rice balance up to 2029. The research workflow is illustrated in the following diagram (see Figure 2).

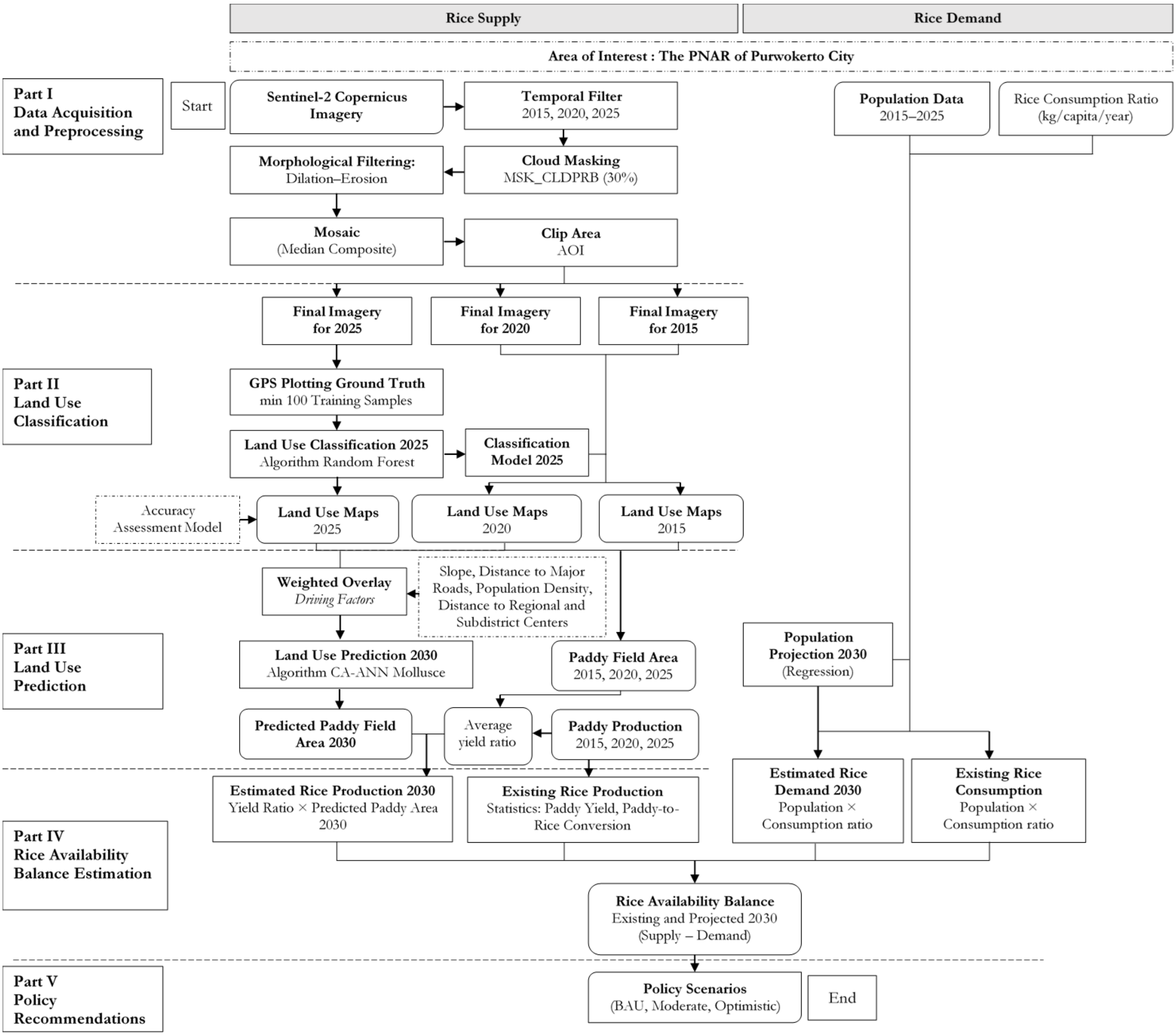

Figure 2. Research Flowchart.

3. Results and Discussion

3.1. Trends in Paddy-field Conversion in The PNAR of Purwokerto (2015–2024)

Model validation was performed using 50 independent ground truth samples representing settlement, paddy field, and non-paddy vegetation classes (Figure 1.b). The Random Forest (RF) classification achieved an overall accuracy of 84% and a Kappa coefficient of 0.71, indicating substantial agreement between classified and observed data. Minor errors occurred in transitional zones where grasslands and fallow plots spectrally resembled paddy fields, a common feature in tropical mosaics. Overall, the RF model showed strong class separability and reliability for temporal modeling. The field-based confusion matrix (Figure 3) confirms this performance, with high producer and user accuracies across major classes and minimal cross-class misclassification.

Further robustness evaluation was conducted using both area- and probability-based transition matrices for two temporal periods: 2015–2019 and 2019–2024 (Figure 4). The 2015–2019 matrix indicated strong class stability, dominated by settlements (3,954 ha; 0.973), paddy fields (7,256 ha; 0.853), and non-paddy vegetation (11,353 ha; 0.903). Reverse transitions of built-up areas were minimal, with only 82 ha (0.020) reclassified as paddy fields and 30 ha (0.007) as non-paddy fields, confirming that classification noise was negligible and that the model retained spatial logic. During 2019–2024, class stability remained high for built-up (4,700 ha; 0.933) and non-paddy fields (11,395 ha; 0.932), while the conversion of paddy fields to settlements increased substantially from 411 ha (0.048) to 1,103 ha (0.140), reflecting genuine urban expansion. Reverse transitions from settlements to paddy (320 ha; 0.064) and to non-paddy fields (19 ha; 0.004) were again minor and spatially scattered. Collectively, the two matrices confirm that the RF classifier maintains temporal robustness and spatial coherence, ensuring that the CA–ANN simulation for 2029 accurately reflects fundamental land use dynamics rather than algorithmic artifacts.

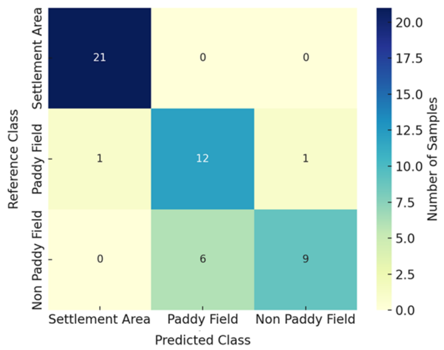

Figure 3. Confusion Matrix Heatmap Showing Class-Level Accuracy and Misclassification Probability for the 2024 Random Forest Model.

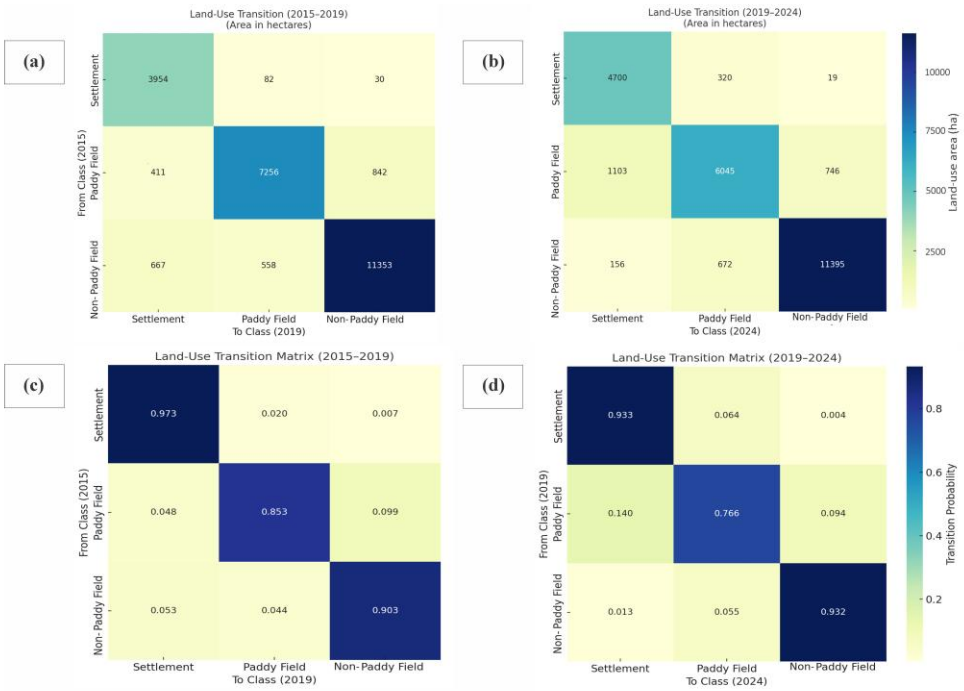

Figure 4. Land use Transition Matrices and Probability Heatmaps Derived from the 2024 Random Forest Classification. Panels (a) and (b) display area-based transition matrices (in hectares) for 2015–2019 and 2019–2024, respectively, while panels (c) and (d) show the corresponding normalized transition probabilities. Darker shades indicate higher stability or greater persistence of each land use class along the diagonal, whereas lighter tones denote cross-class transitions and misclassification probabilities.

Temporally, land use dynamics between 2015 and 2024 reveal a pronounced and systematic transformation in the PNAR of Purwokerto, marked by a substantial expansion of settlement areas and a consistent contraction of paddy-field extent. According to the statistical recapitulation (Figure

5), built-up areas increased sharply from 4,068.87 ha in 2015 to 5,960.98 ha in 2024, representing an overall growth of approximately 46.5 percent within less than a decade. In contrast, paddy-field coverage exhibited a continuous decline, dropping from 8,506.19 ha in 2015 to 7,893.43 ha in 2019 (−612.76 ha), and further to 7,040.78 ha in 2024 (−852.65 ha). The cumulative loss of 1,465.41 ha over the ten years underscores an accelerating land conversion process primarily driven by rapid urban growth and infrastructure development. Meanwhile, the non-paddy-field category remained relatively stable, fluctuating only slightly from 12,577.80 ha in 2015 to 12,151.10 ha in 2024, suggesting that paddy-field loss occurred predominantly within the rural–urban transition belt rather than through large-scale vegetation clearance.

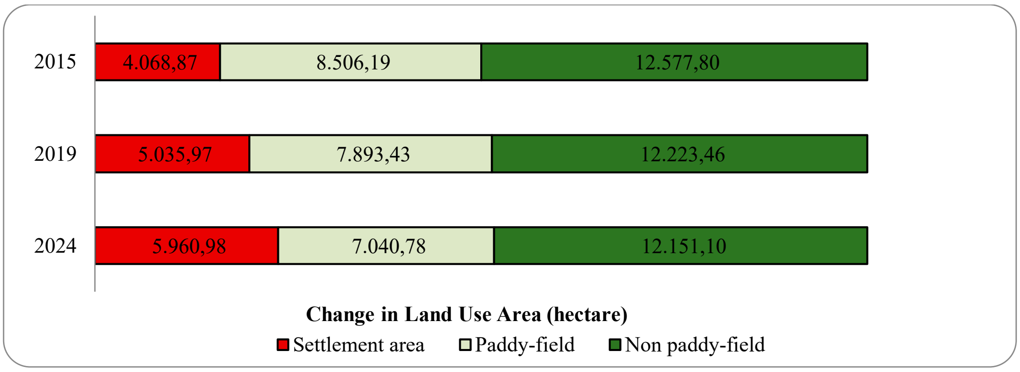

Figure 5. Land Use Area Changes in 2015, 2019, and 2024.

Spatially, the expansion of settlement areas follows a concentric diffusion pattern radiating outward from the Purwokerto urban core (Figure 6). The most significant outward trajectories are observed toward the east (Kembaran), south (Purwokerto Selatan), north (Baturaden), southwest (Karanglewas), and northwest (Sumbang), reflecting both clustered and linear growth forms. These patterns indicate an ongoing process of urban sprawl that extends beyond the limits of formal spatial planning, in which productive agricultural land, particularly paddy fields, constitutes the most vulnerable target for conversion. Two distinct morphologies of expansion can be discerned: (1) compact or clustered development within the central urban core, driven by residential densification and infill; and (2) linear sprawl along primary transportation corridors connecting Purwokerto to its surrounding subdistricts. This configuration aligns with the findings of Munibah *et al*. (2024), confirming the strong influence of accessibility and spatial hierarchy in accelerating conversion pressures.

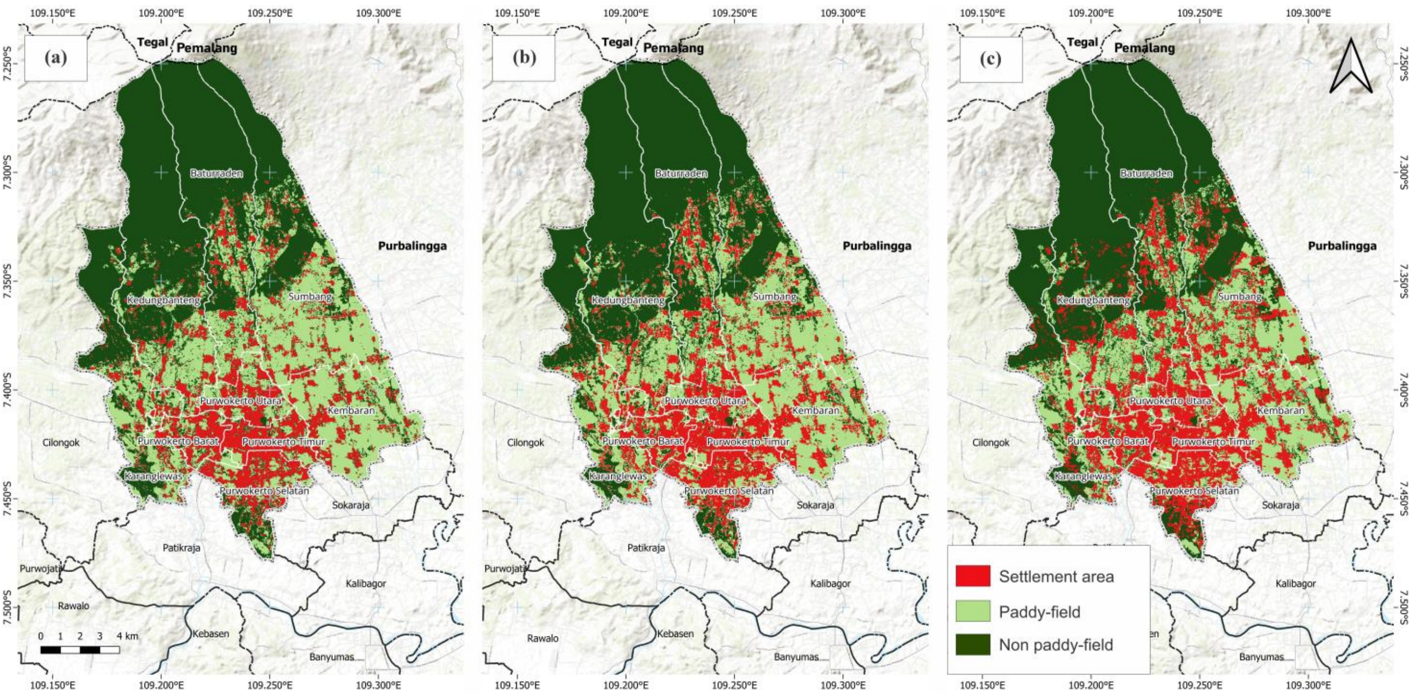

Figure 6. Spatial Land Use Change Map for 2015 (a), 2019 (b), and 2024 (c).

Building upon these regional transitions, subdistrict-level evaluation (Figure 7) provides a more detailed understanding of paddy-field dynamics by isolating the pure agricultural extent regardless of conversion destination. The data show an uneven but alarming decline across the PNAR. The most significant reduction occurred in Sumbang (516.3 ha), followed by Kembaran (243.7 ha), Kedungbanteng (177.5 ha), and Karanglewas (98.7 ha), all of which historically served as the agrarian buffer of Purwokerto. The persistent contraction of active paddy-field areas across these outer subdistricts signifies that development pressure has advanced beyond the city limits, fragmenting what was once a contiguous rice-producing landscape into a mosaic of residential, commercial, and semi-urban land uses.

Within the inner urban subdistricts of Purwokerto Selatan, Barat, Timur, and Utara, the remaining paddy-field area has declined to critically low levels, each representing less than 4 percent of its administrative territory. By 2024, Purwokerto Selatan retained only 287.7 ha (2.05 %), Timur 186.18 ha (2.23 %), Barat 205.64 ha (2.61 %), and Utara 318.42 ha (3.29 %), highlighting the near disappearance of agrarian land within the city's core. Overall, paddy-field coverage across the PNAR declined from 8,506.19 ha (33.82 %) in 2015 to 7,040.78 ha (27.99 %) in 2024, an unmistakable sign of spatial attrition that precedes direct conversion. This pattern illustrates that the depletion of agricultural land itself has reached a critical stage, providing a quantitative basis for analyzing paddy-field-to-settlement conversion dynamics in the following section.

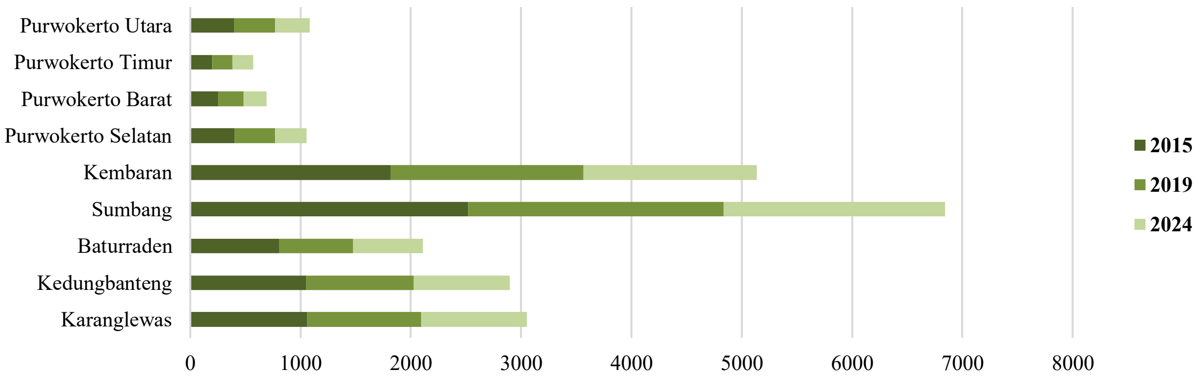

Figure 7. Distribution of Paddy-field Area Change in 2015, 2019, and 2024.

Building on previous findings, the transition analysis (Figure 8) quantifies the extent to which this agricultural decline corresponds directly to settlement conversion, isolating the urbanization-driven component of land transformation. The conversion rate of paddy fields to settlements rose dramatically from 410.39 ha (102.6 ha yr^{-1} or 1.63 %) during 2015–2019 to 1,105.03 ha (221.0 ha yr^{-1} or 4.39 %) during 2019–2024, a 115 percent increase in annual conversion intensity. This acceleration coincides with the surge in post-2019 residential and infrastructure projects, particularly along the Purwokerto–Kembaran–Sumbang growth corridor, now functioning as the dominant axis of urban expansion. In relative terms, conversion shares more than doubled across all subdistricts, from 0.75–4.04 % in the first period to 2.73–7.54 % in the second, confirming both temporal and spatial intensification of land transformation.

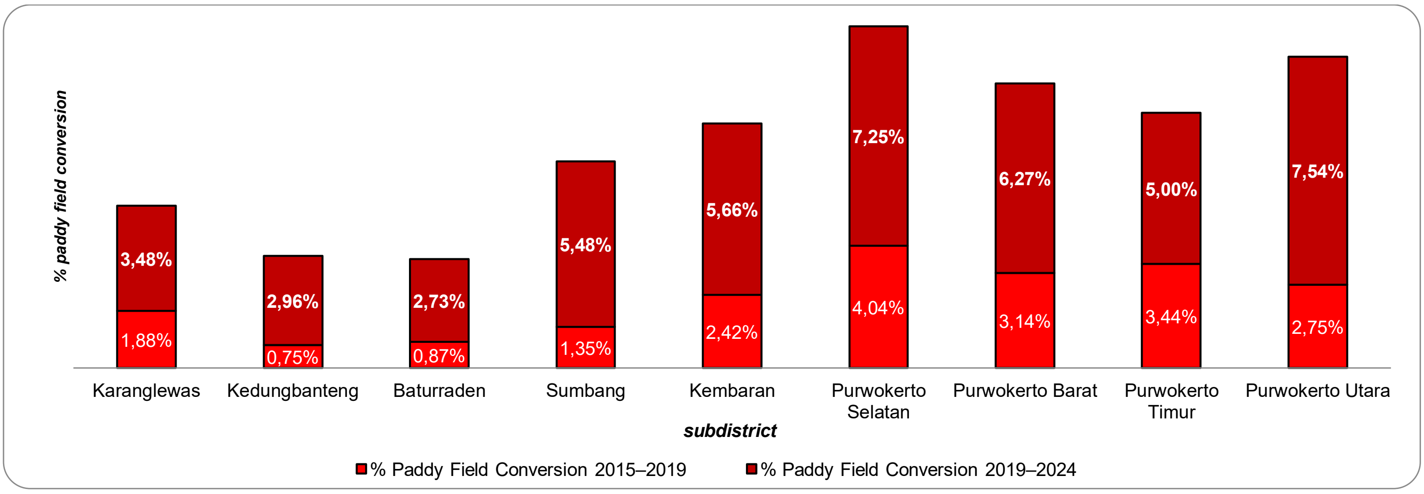

Figure 8. Percentage of Paddy-Field Conversion to Settlement Areas across Subdistricts in 2015–2019 and 2019–2024.

Spatially, these dynamics reflect a dual morphological trajectory, urban densification within the core and peripheral sprawl in the outer subdistricts. In the core area, Purwokerto Selatan increased from 56.65 to 101.62 ha (equivalent to a rise from 4.04 to 7.25 percent), Purwokerto Utara from 26.63 to 72.90 ha (2.75 to 7.54%), and Purwokerto Timur from 28.79 to 41.76 ha (3.44 to 5.00%), indicating rapid infill growth driven by the exhaustion of vacant plots and the conversion of remaining paddy patches into residential areas. In the outer fringe, Sumbang expanded from 74.24 to 301.56 ha (1.35 to 5.48%), Kembaran from 61.49 to 143.79 ha (2.42 to 5.66%), Kedungbanteng from 41.31 to 163.84 ha (0.75 to 2.96%), and Karanglewas from 57.17 to 105.82 ha (1.88 to 3.48 percent), marking the outward progression of low-density urban sprawl into former agricultural hinterlands. Baturraden, constrained by steeper slopes, experienced more limited conversion, increasing from 39.44 to 124.45 ha (0.87 to 2.73%). Collectively, these patterns emphasize an intensified core–periphery gradient of urbanization: densification now dominates the urban center. At the same time, outward expansion extends across peri-urban transition belts, progressively eroding the agrarian base and heightening ecological vulnerability.

In several hotspot subdistricts such as Sumbang, Kembaran, Baturraden, and Purwokerto Selatan, field validation confirms that many new residential clusters have emerged directly atop former paddy fields (Figure 9). These findings highlight the tangible encroachment of settlement construction on productive agricultural land and reinforce the spatial correlation between urban growth and agricultural loss. Meanwhile, core subdistricts: Purwokerto Timur, Barat, and Utara, though smaller in absolute area, remain strategically critical due to their high population density and increasing land fragmentation, which collectively accelerate infill and reduce the remaining agricultural resilience.

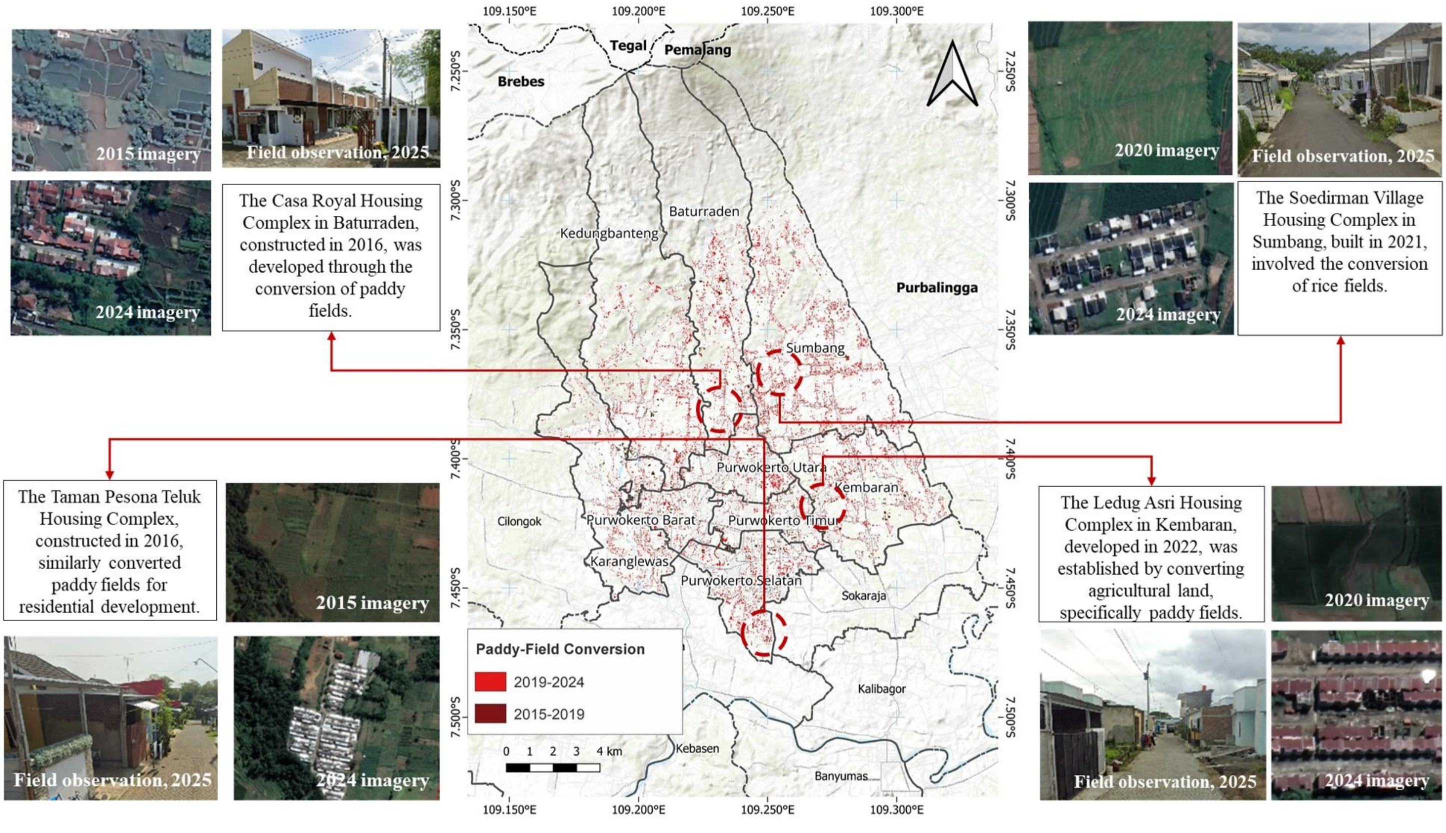

Figure 9. Paddy-field Conversion Maps in 2015–2024.

Overall, paddy field conversion over the past decade has not only increased in volume but also driven urban dispersal into peripheral zones. Without more progressive and spatially informed land use policies, the loss of productive land risks becoming irreversible, threatening local food security and undermining the agrarian foundation of transitional regions such as Purwokerto.

3.2. Predicted Paddy-field Area in 2029 in the PNAR of Purwokerto

Land use prediction for the year 2029 in the PNAR of Purwokerto was developed using a spatial modeling approach that integrates Cellular Automata–Artificial Neural Network (CA–ANN). This approach combines historical land use data from 2019 and 2024 as inputs, along with five driving factors that determine the direction of spatial change. These variables include slope (Figure 10.a), distance to roads (Figure 10.b), population density (Figure 10.c), distance to regional activity centers (Figure 10.d), and distance to subdistrict activity centers (Figure 10.e), each weighted based on its vulnerability to paddy-field conversion into settlement areas. The integration process was conducted using a weighted overlay technique, resulting in a land conversion vulnerability map that served as the basis for predicting land use changes in 2029.

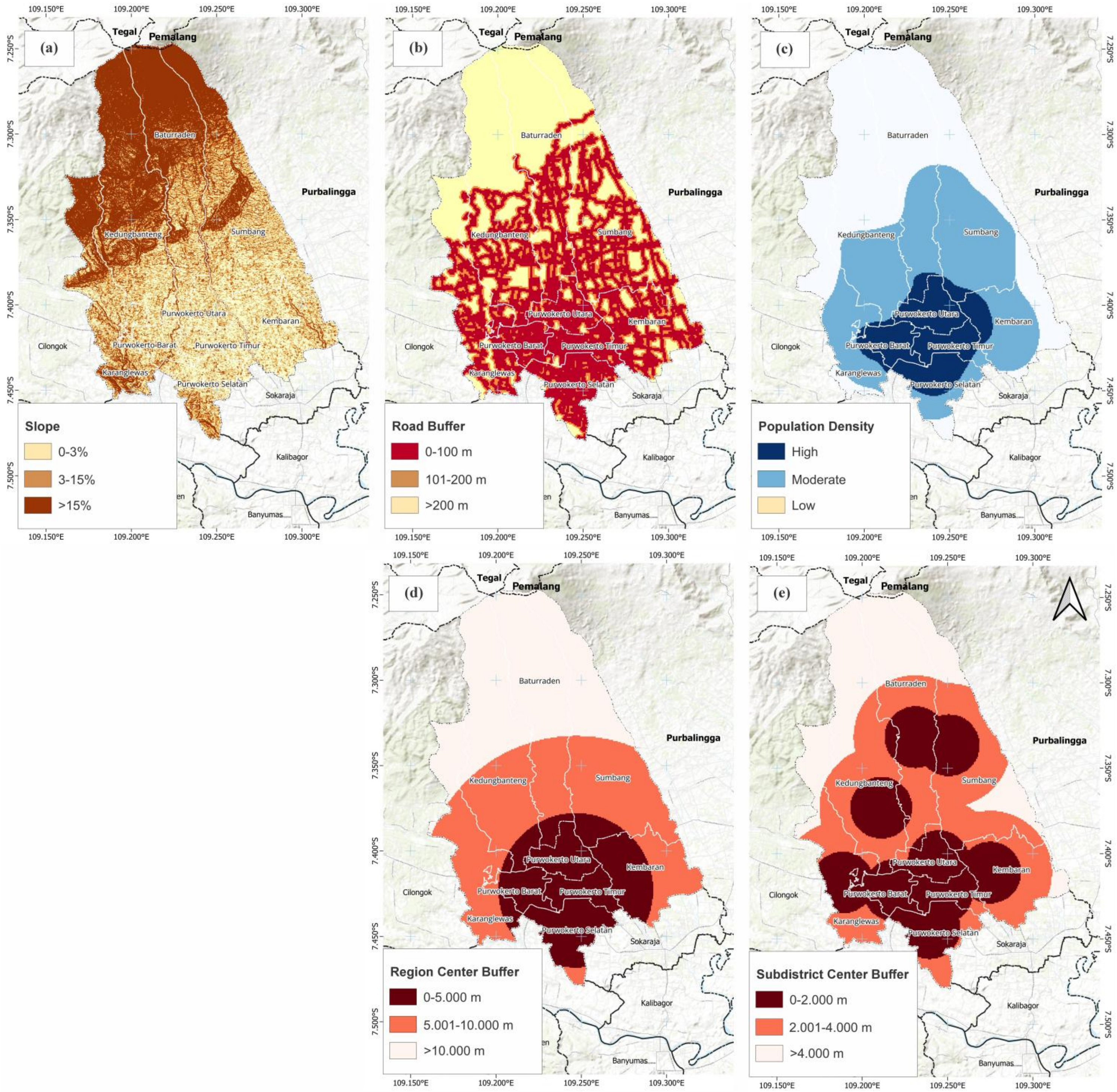

Figure 10. Driving Factors for Land Use Prediction in 2029: (a) Slope; (b) Road Proximity; (c) Population Density; (d) Regional Center Buffer; (e) Subdistrict Center Buffer.

Specific biophysical and socio-economic characteristics play a pivotal role in driving land conversion dynamics within peri-urban landscapes. Areas with low slope gradients (0–3%) are more prone to conversion due to ease of access and high construction feasibility. Likewise, locations situated within a 100-meter buffer from major roads are prioritized for development, benefiting from superior transport connectivity. Furthermore, zones with high population density, particularly those in proximity to regional and local growth centers (regional center and subdistrict center), face intense spatial pressure on remaining agricultural lands. The convergence of favorable topographic conditions, infrastructural accessibility, demographic stress, and nearness to growth hubs positions these areas as potential hotspots for future land use transformation and (Pratami et *al.,* 2019; Sugandhi *et al.,* 2022).

Figure 11 integrates spatial and quantitative perspectives to clarify the linkage between conversion potential and simulated land use. Panel (a) highlights high-conversion zones (in red) representing areas under strong accessibility and demographic pressures, while green areas indicate low susceptibility due to ecological or topographic constraints. Panel (b) presents the 2029 CA–ANN simulation results, showing how these pressures translate into actual settlement expansion and paddy-field decline. The spatial correspondence between both panels confirms that areas with flat terrain, dense populations, and high accessibility are the most vulnerable to urban encroachment, reinforcing the spatial logic and explanatory robustness of the CA–ANN model under the Business-as-Usual scenario in the PNAR of Purwokerto.

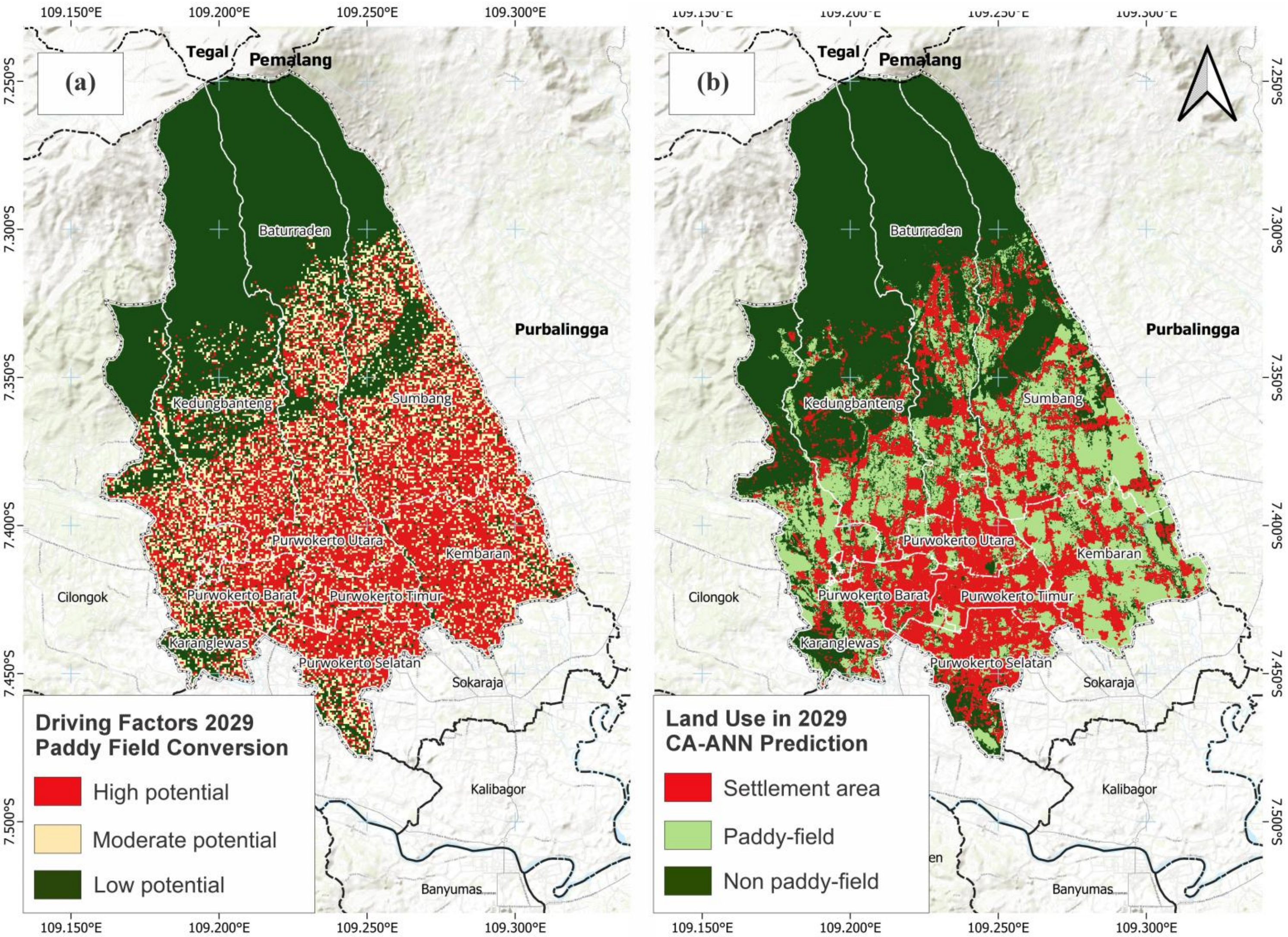

Figure 11. Spatial Driving Factors for Land Use Change and Predicted Land Use in 2029 within the PNAR of Purwokerto: (a) Spatial distribution of driving factors; (b) Predicted land use map for 2029 based on CA–ANN simulation.

Using the Tabulate Area analysis in QGIS, the 2024 paddy-field extent was intersected with reclassified driving-factor layers to compute the total area (in hectares) and the percentage distribution by class. Results show that approximately 3,920 ha (49%) of paddy fields are located on slopes below 3%, 3,425 ha (43%) lie within 100 m of major roads, and 4,476 ha (56%) are situated in high-density settlement zones, confirming that a large share of agricultural land already overlaps with zones of elevated conversion pressure. In contrast, only 934 ha (12%) occur on steeper terrain (>15%), and less than 1,440 ha (18%) are located beyond 200 m from main roads, suggesting that spatial refuges from urban encroachment are becoming increasingly limited. The detailed hierarchical structure of these driving factors and their suitability classes is illustrated in the sunburst diagram (Figure 12), which visualizes the relative contribution of each factor to the overall spatial conversion potential.

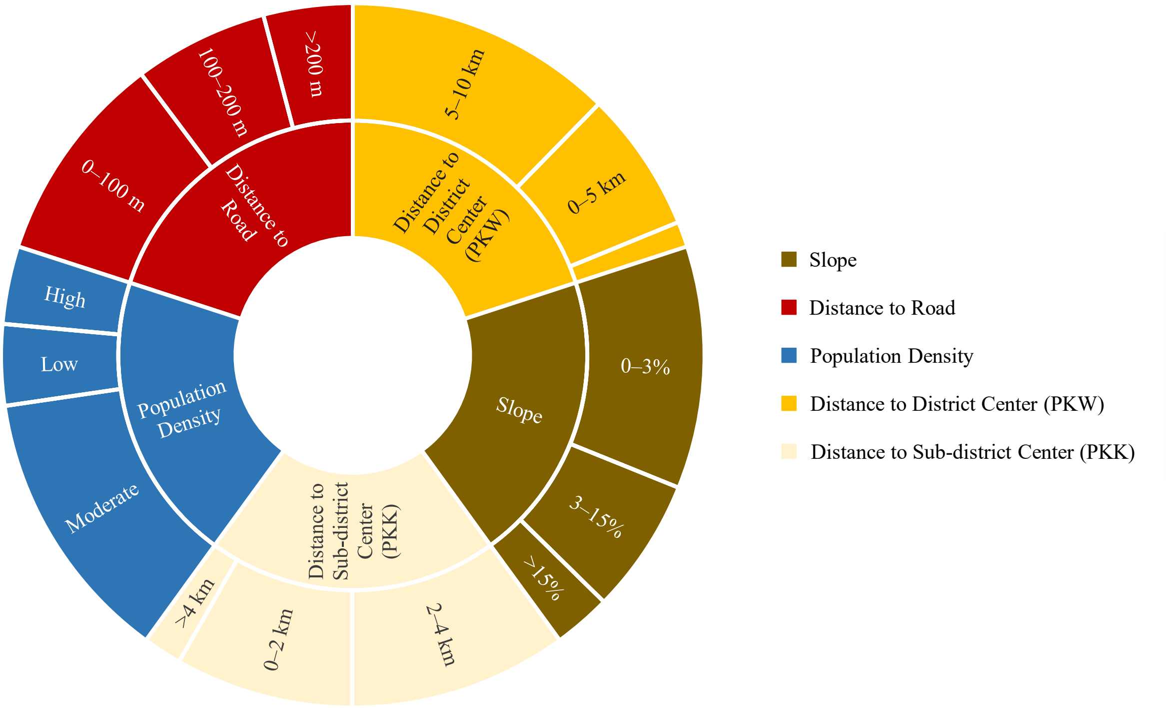

Figure 12. Classification Scheme of Spatial Driving Factors Used in the CA–ANN Model for 2029 Land Use Simulation.

According to the CA–ANN simulation results (Figure 11b), the extent of paddy fields is projected to decrease from 7,040.78 ha in 2024 to 6,511.94 ha in 2029, marking a loss of about 528.84 ha, or 7.5% within five years. Although the rate of decline appears slower than in the previous period, this moderation primarily reflects the diminishing availability of easily convertible land. Most low-lying, highly accessible paddy fields near major road corridors and urban centers have already been transformed in earlier phases, leaving fewer plots within the current urbanization frontier. Consequently, recent expansion tends to occur in smaller, fragmented patches dispersed across peri-urban areas, which slows the aggregate conversion rate while still indicating persistent spatial pressure on productive agricultural land (Figure 13a).

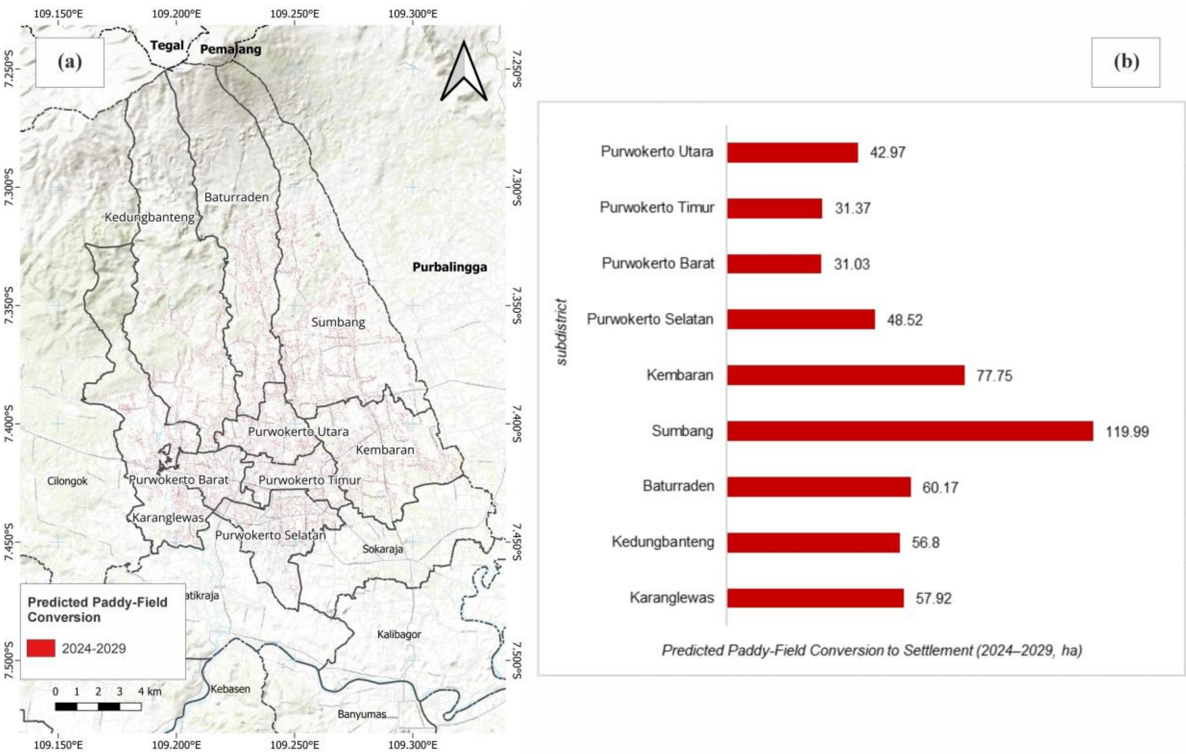

Figure 13. Projected Paddy Field Conversion by Subdistrict in 2029: (a) Spatial Distribution Map of Projected Conversion Hotspots; (b) Bar Chart Showing Total Converted Area per Subdistrict (in Hectares).

The total conversion share decreases from 4.39% to 2.09% of the PNAR's total area, equivalent to approximately 526.52 ha of paddy fields converted into settlement areas. Sumbang remains the dominant conversion hotspot, with 119.99 ha (2.18%) of its territory projected to transition to settlement areas, thereby maintaining its role as the principal expansion front. Kembaran follows with 77.75 ha (3.06%), while Purwokerto Utara (42.97 ha; 4.44%), Purwokerto Barat (31.03 ha; 3.95%), Purwokerto Timur (31.37 ha; 3.75%), and Purwokerto Selatan (48.52 ha; 3.46%) continue to experience significant infill within the urban core. In contrast, outer subdistricts such as Karanglewas (57.92 ha; 1.90%), Kedungbanteng (56.80 ha; 1.03%), and Baturraden (60.17 ha; 1.32%) show relatively minor but spatially scattered conversion patches, reflecting a shift toward fragmented development along secondary road networks. These projections suggest that while the pace of overall conversion may appear to decelerate, the spatial extent of settlement expansion continues to encroach upon the remaining agricultural land, particularly along mixed urban–rural interfaces. By 2029, under the Business-as-Usual (BaU) scenario, the total paddy-field area is expected to decline to just 6,511.94 ha, equivalent to only 25.9% of the PNAR's total land area, signaling a critical reduction in the region's agrarian base and intensifying challenges for local rice self-sufficiency.

3.3. Existing Rice Availability Balance in the PNAR of Purwokerto

The relationship between paddy-field area and rice production in the PNAR of Purwokerto exhibits a robust, consistent correlation over time. Based on linear regression analysis, the coefficient of determination (R^2) values were 0.9093 in 2015, 0.8518 in 2019, and 0.8327 in 2024. The average R^2 value of 0.8647 indicates that changes in paddy-field area can explain more than 86% of the variation in rice production. This positive correlation confirms that paddy fields remain the primary and decisive input in maintaining regional rice production capacity. The decline in paddy-field area from 8,506.19 ha (2015) to 7,040.78 ha (2024) is reflected in the corresponding drop in rice production, from 95,148.10 tons to 80,148.52 tons. This indicates that land conversion directly weakens local food security by reducing production potential.

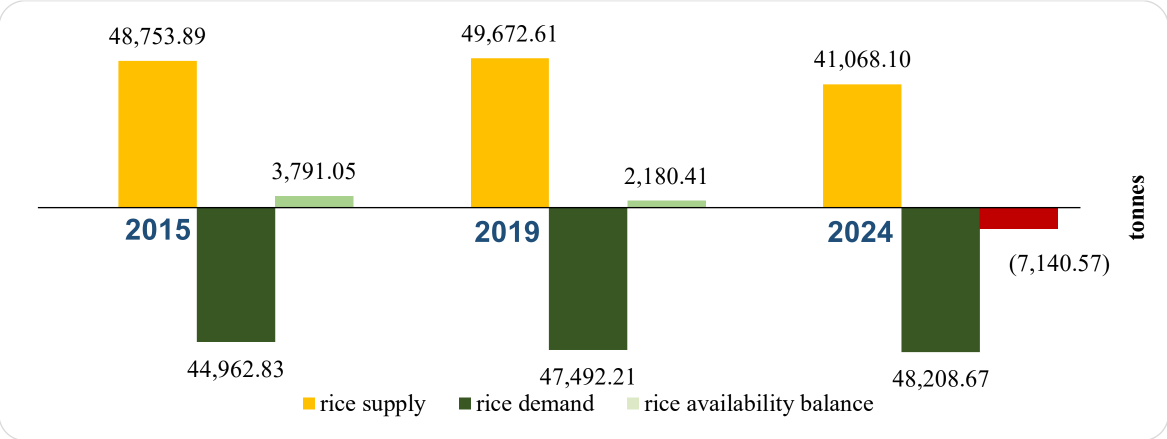

Figure 14. Existing Rice Availability Balance in the PNAR of Purwokerto.

To assess the sustainability of the food system, a rice availability balance was calculated using a paddy-to-rice conversion rate of 51.24% (BPS) and a per capita rice consumption rate of 79.08 kg/year based on national food standards (Bapanas). The results show a surplus of 3,791.05 tons in 2015, decreasing to 2,180.41 tons in 2019, and shifting to a significant deficit of −7,140.57 tons in 2024 (Figure 14). This decline highlights an alarming trend in which the population growth, reaching 609,619 people in 2024, is not matched by adequate rice supply capacity. What was once a self-sufficient production system is no longer sufficient to meet local needs, with a wide deficit margin indicating increasing dependence on external supply sources.

Furthermore, spatial disparities between rice supply and demand needs are most evident in urban districts such as the four districts of Purwokerto. Although these districts serve as administrative and economic hubs, each has fewer than 400 ha of paddy fields and a rapidly growing population. As a result, they face significant food deficits. In 2024, Purwokerto Selatan recorded a deficit of −4,989 tons, Purwokerto Barat −3,603 tons, Purwokerto Timur −3,945 tons, and Purwokerto Utara −3,434 tons. These disparities reveal that an urbanization-driven development model that neglects the protection of food-producing areas has created spatial dysfunction in the local food security system.

Meanwhile, agrarian areas such as Sumbang, Kedungbanteng, and Kembaran remain the main contributors to rice supply, with surpluses of 2,224 tons, 3,639 tons, and 1,802 tons, respectively, in 2024. However, signs of declining production are also emerging in these regions, driven by increasing pressure from land conversion and population growth. If this trend is not controlled, the PNAR in Purwokerto will likely rely entirely on external food supplies, undermining the autonomy and sustainability of the local food system.

These findings affirm that regional food security depends directly on the spatial protection of paddy fields. The persistent rice deficit amid rapid population growth and land conversion signals a structural crisis requiring urgent intervention. Policies should prioritize the designation of Sustainable Food Agricultural Land, stricter spatial regulation of conversion, and the promotion of intensive small-scale urban agriculture. Without such integrative measures, dependence on external food sources will deepen, undermining long-term regional resilience.

3.4. Rice Self-Sufficiency Scenarios in the PNAR of Purwokerto in 2029

To anticipate future food security challenges in the PNAR of Purwokerto, a simulation of the 2029 rice availability balance was conducted based on three spatial and demographic management scenarios: BaU, Moderate, and Optimistic. These scenarios are based on three key variables: the rate of paddy-field conversion, population growth, and the increase in the cropping index (CI), as shown in Table 2.

Table 2. Rice Self-Sufficiency Scenarios in the PNAR of Purwokerto in 2029.

Variabel	BaU	Moderate	Optimistic
Cropping Index	Remains 200	Increased to 250	Increased to 300
Population Growth	As projected (648,490 people)	Reduced by 4% (622,550 people)	Reduced by 5% (616,066 people)
Paddy-field Area	As predicted (6,511.94 ha)	Reduced by 2% (6,642.18 ha)	Reduced by 4% (6,772.42 ha)

The BaU scenario represents a no-intervention condition, assuming the CI remains at 200, the paddy-field area declines to 6,511.94 ha, and the population increases to 648,490. The Moderate scenario assumes controlled urban expansion, with CI increased to 250, a 2% reduction in paddy-field conversion (to 6,642.18 ha), and a 4% reduction in population growth, resulting in a population of 622,550. The Optimistic scenario represents maximum intervention: CI is raised to 300, paddy-field conversion is reduced by 4% (to 6,772.42 ha), and population growth is further reduced by 5%, resulting in 616,066 people.

Under the BaU scenario, the rice availability balance is projected to face a significant deficit of −12,520.54 tons (Figure 15). This is due to a combination of shrinking paddy-field area and stagnant productivity (CI remains at 200), producing only 75,648.03 tons of paddy or 38,762.05 tons of rice. Meanwhile, rice demand reaches 51,282.59 tons due to population growth. Spatially, all central urban districts face severe deficits, including Purwokerto Selatan (−5,651.25 tons), Purwokerto Barat (−3,636.65 tons), and Purwokerto Timur (−4,171.02 tons), reflecting a structural imbalance between consumption centers and production areas. Even agriculturally based districts such as Karanglewas and Baturraden are under pressure, with small surpluses of only 23.27 and 276.13 tons, respectively.

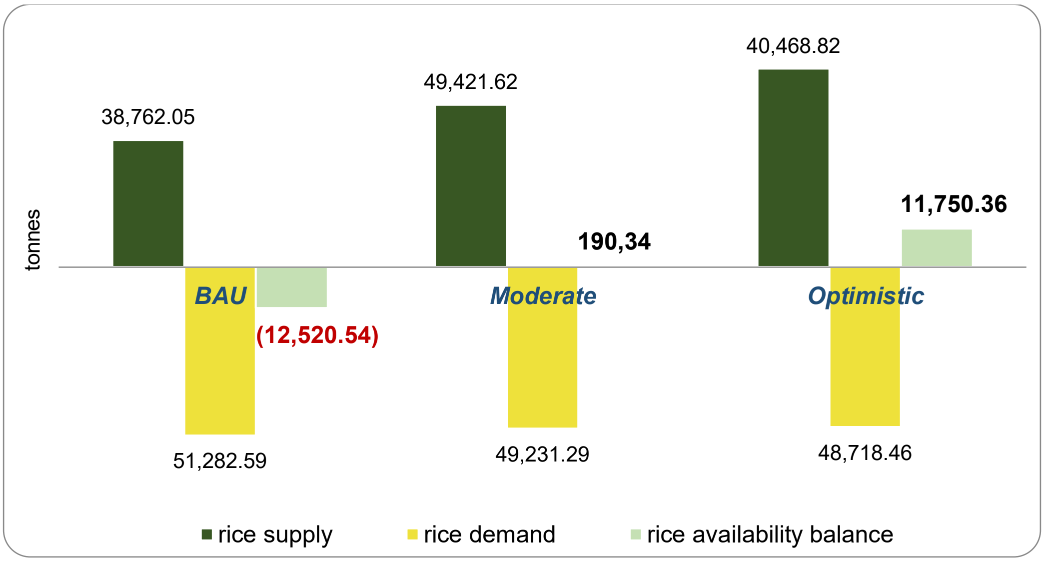

Figure 15. Rice Self-Sufficiency Scenarios in the PNAR of Purwokerto in 2029.

The Moderate scenario yields much more stable results. With moderate controls on housing expansion and population growth, combined with a higher CI of 250, paddy production increases to 96,451.24 tons, or 49,421.61 tons of rice. With a projected rice demand of 49,231.29 tons, the overall rice availability balance is nearly even, with a slight surplus of 190.34 tons. Spatial disparities remain in core urban areas such as Purwokerto Selatan (−5,219.85 tons), Purwokerto Barat (−3,199.89 tons), and Purwokerto Timur (−3,832.65 tons). However, these deficits are offset by large surpluses from agrarian areas such as Sumbang (+4,624.46 tons), Kedungbanteng (+3,826.65 tons), and Kembaran (+2,955.41 tons). These results indicate that even limited interventions can stabilize the rice balance when implemented in a planned, integrated manner.

The Optimistic scenario offers the most promising outcome. With CI increased to 300, paddy-field conversion limited to 6,772.42 ha, and population capped at 616,066, paddy production surges to 118,010.93 tons, equivalent to 60,468.80 tons of rice. At the same time, rice demand is only 48,718.46 tons. Consequently, the PNAR of Purwokerto has the potential to achieve a rice surplus of +11,750.36 tons by 2029. Agrarian districts emerge as the key buffers, with significant surpluses from Sumbang (+7,535.05 tons), Kedungbanteng (+5,911.05 tons), Kembaran (+5,202.18 tons), Karanglewas (+3,633.56 tons), and Baturraden (+3,253.26 tons).

Managing population growth and intensifying production can effectively reverse the trend from food deficits to balance or surplus. Therefore, the Moderate and Optimistic scenarios are not mere idealizations but provide a concrete foundation for long-term policy decisions aimed at achieving sustainable regional food security.

3.5. Discussion

This study demonstrates that paddy-field conversion in the PNAR of Purwokerto has evolved systematically and intensified over the past decade, reflecting the classic pattern of peri-urban sprawl consistent with Munibah et al. (2024). Although Purwokerto has not yet been formally designated as a new autonomous region, its functional urban expansion already exhibits the characteristics of an emerging city region. However, evidence from the PNAR highlights a critical trade-off: while infrastructure development and modernization have accelerated, they have simultaneously driven extensive farmland conversion, undermining regional food security. This dynamic mirrors global experiences in peri-urban areas, where development fosters opportunity yet deepens vulnerability (Allen, 2003; Simon, 2008). Urban expansion, though an inevitable aspect of modernization, can either strengthen resilience or amplify systemic risk, depending on how it is governed. The convergence of urban and agricultural land uses thus creates contested spaces where competing priorities collide. Without robust spatial regulation and food-sensitive planning, transitional zones risk becoming structurally fragile, reinforcing urban bias and exacerbating food insecurity (Michael, 1976; Seto *et al.,* 2012).

Beyond area loss, land conversion signifies a degradation in spatial quality and production capacity. Between 2015 and 2024, paddy fields declined from 8,506 ha to 7,041 ha. Projections indicate a further reduction to 6,512 ha by 2029. Every 100 hectares converted corresponds to approximately 767 tons of lost rice output (Figure 13), underlining the direct link between spatial transformation and systemic vulnerability. As land conversion continues, the regional rice balance deteriorates, shifting from a surplus in 2015 (+3,791 tons) to a deficit in 2024 (−7,141 tons), and potentially reaching a deficit of −12,520 tons by 2029. These results support the food–land nexus framework (Cumming *et al.,* 2014) which emphasizes that spatial integrity, resource governance, and production systems underpin food security. Comparable trade-offs have been documented in China, the Philippines, and Sub-Saharan Africa, where rapid peri-urban growth has undermined agricultural resilience, increasing reliance on imports and exposure to market fluctuations (Dumdumaya & Cabrera, 2023; Molla *et al.,* 2024; Park *et al.,* 2024).

This regional vulnerability mirrors Indonesia's broader food security challenges, as dependence on imports of national rice has surged in recent years. In 2024, Indonesia imported over 4.5 million tons of rice, an elevenfold increase from 2019 (444,508 tons), with a CIF value reaching US$2.71 billion, the highest in eight years. The escalation stems from domestic production shortfalls driven by farmland loss and climate disruptions. Continued conversion of productive paddy fields, such as in the PNAR Purwokerto, risks compounding local deficits into systemic national shortages and deepening dependence on volatile global markets. This feedback loop, in which shrinking domestic capacity fuels greater reliance on imports, underscores that the spatial fragility observed in PNAR reflects a structural national risk. Safeguarding peri-urban agricultural land is therefore not merely a regional issue but a strategic imperative for sustaining Indonesia's long-term food resilience.

Underlying this trajectory is a structural governance deficit. Although Indonesian Law No. 41/2009 mandates the protection of agricultural land to ensure food security, enforcement in transitional regions remains weak. Fragmented institutional authority and poorly coordinated spatial plans create a regulatory gap that allows speculative development to outpace policy control. As a result, farmland protection becomes nominal, mainly with regulations existing in form but not in effect. According to peri-urban resilience theory, such governance fragility reflects low adaptive capacity, where misaligned policies and weak institutional responsiveness expose regions to systemic risks (Allen, 2003; Woltjer, 2014). The implications extend beyond food insecurity to socio-economic fragility, as rapid land conversion without livelihood alternatives deepens agrarian distress and widens rural–urban inequality. Similar urban-biased development patterns in Africa and South Asia (Simon, 2008) show that unless food security objectives are embedded within spatial governance, the PNAR of Purwokerto risks reproducing unsustainable and inequitable growth trajectories.

Scenario modeling illustrates that without intervention, the PNAR's rice deficit could deepen to −12,520 tons by 2029. While modest gains in CI offer partial relief, they cannot offset ongoing farmland loss. A moderate scenario combining CI 250, a 2% reduction in land conversion, and a 4% slowdown in population growth stabilizes the rice balance near equilibrium (+190 tons), whereas a surplus under the optimistic case would demand major governance and behavioral reforms.

These findings highlight that technological improvements alone are insufficient; effective land use control and demographic management are essential to curb agricultural decline. Global experiences from Shanghai, Tokyo, and Havana show that enforceable zoning, fiscal incentives, and food-sensitive spatial planning can harmonize urban growth with farmland preservation (Skar *et al.,* 2020).

The implications for governance are far-reaching. Addressing the trade-offs in the PNAR of Purwokerto requires a coordinated, proactive, and integrated policy framework that aligns spatial planning with food system resilience. Farmland protection must become a core governance priority. This involves enforcing Law No. 41/2009 through binding agricultural zones in the Regional Spatial Plan, strengthened by tax incentives for active farming, penalties for illegal conversion, and GIS-based monitoring to identify high-risk conversion areas.

Additionally, production intensification must complement regulatory efforts. Boosting CI to 250 using high-yield, short-duration rice varieties (e.g., Inpari 32, Mekongga) and mechanized rotations can improve yields. These practices require reliable input subsidies, extension services, and efficient micro-irrigation to ensure viability. Population pressure also plays a role. Community-based family planning programs (e.g., Kampung KB) and reproductive health education can help slow demographic growth in high-risk peri-urban districts. Finally, economic diversification can reduce conversion incentives. Agrotourism and high-value horticulture can provide alternative income streams for rural households, easing pressure on land resources. Together, these approaches represent a comprehensive response to the multidimensional risks facing the PNAR.

Ultimately, the PNAR of Purwokerto exemplifies the broader urban–agrarian paradox observed across Indonesia's secondary cities, where decentralization stimulates economic growth yet simultaneously undermines agrarian resilience. The integrative modeling framework, combining remote sensing, land use simulation, and rice balance analysis, serves as both a diagnostic and planning instrument for evidence-based policy. Its approach is transferable to other rapidly urbanizing cities in the Global South, particularly those undergoing decentralization and facing similar tensions between development and food system sustainability.

4. Conclusion

Urban expansion in the PNAR of Purwokerto exemplifies the structural trade-offs between economic growth and food system resilience in peri-urban landscapes. This study demons-trates that systematic paddy field conversion, shrinking from 8,506 ha in 2015 to a projected 6,512 ha by 2029, has shifted the regional rice balance from a surplus of +3,791 tons in 2015 to a deficit of −7,141 tons in 2024, with the BaU trajectory forecasting a severe shortfall of −12,520 tons by 2029. Every 100 hectares converted results in an estimated loss of 767 tons of potential rice production, underscoring the tangible cost of unchecked spatial change.

The scenario-based modeling framework reveals that technological interventions alone, such as increasing the CI, cannot fully compensate for these losses. The Moderate scenario, integrating a CI of 250, a 2% reduction in land conversion, and a 4% reduction in population growth, achieves near balance (+190 tons), whereas the Optimistic scenario delivers substantial surpluses but requires structural changes unlikely to materialize in the short term. These findings highlight that safeguarding food security in rapidly urbanizing regions necessitates integrated strategies combining land use regulation, production intensification, and demographic management.

Beyond providing a risk diagnosis, the integrated spatial–aspatial modeling framework developed in this study advances planning toward predictive and prescriptive capacities, offering a transferable decision-support tool for other Global South regions facing similar urban–agricultural trade-offs. Future research should incorporate agro-climatic and institutional dimensions to enhance policy realism and governance relevance. Ultimately, the decisions made today will determine whether emerging city regions evolve into resilient urban systems or descend into structural food insecurity and socio-economic fragility.

Acknowledgements

The author extends sincere gratitude to the lecturers and coordinators of the Field Study course in the Department of Geography, Universitas Indonesia, for their invaluable guidance throughout the research process. Appreciation is also given to Bappeda and the Department of Agriculture of Banyumas Regency for providing essential data and facilitating field access. Special thanks go to the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance, for funding the author's academic journey and supporting this research. The author is also grateful to all individuals and institutions who contributed to the completion of this study.

Author Contributions

Conceptualization: Rizqi, B., & Manessa, M. D. M; **methodology:** Rizqi, B.; **investigation:** Rizqi, B., & Manessa, M. D. M; **writing—original draft preparation**: Rizqi, B. **M; writing—review and editing:** Rizqi, B., & Manessa, M. D. M; **visualization:** Rizqi, B., & Manessa, M. D. M. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by Indonesia Endowment Fund for Education (LPDP).

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

References

Ahmed, N., & Turchini, G. M. (2021). The evolution of the blue-green revolution of rice-fish cultivation for sustainable food production. *Sustainability Science,* 16(4), 1375–1390. doi: 10.1007/s11625-021-00924-z

Alikhanov, B., Pulatov, B., & Samiev, L. (2024). The Detection of Past and Future Land Use and Land Cover Change in Ugam Chatkal National Park, Uzbekistan, Using CA-Markov and Random Forest Machine Learning Algorithms. *Forum Geografi,* 38(2), 121–137. doi: 10.23917/FORGEO.V38I2.4221

Allen, A. (2003). *Environmental planning and management of the peri-urban interface: perspectives on an emerging field.* Retrieved From www.ucl.ac.uk/dpu/pui

Arfasa, G. F., Owusu-Sekyere, E., & Doke, D. A. (2023). Predictions of land use/land cover change, drivers, and their implications on water availability for irrigation in the Vea catchment, Ghana. *Geocarto International,* 38(1). doi: 10.1080/10106049.2023.2243093

Audina Irawan, I., Supriatna, S., Manessa, M., & Ristya, Y. (2019). *Prediction Model of Land Cover Changes using the Cellular Automata – Markov Chain Affected by the BOCIMI Toll Road in Sukabumi Regency. KnE Engineering.* Retrieved From https://doi.org/10.18502/keg.v4i3.5860

Ayalew, S. E., & Nigussie, T. A. (2023). Historical and projected land use / land cover changes of the Welmel River Watershed, Genale Dawa Basin, Ethiopia. *Journal of Water and Land Development,* 58, 89–98. doi: 10.24425/jwld.2023.146601

Baig, M. F., Mustafa, M. R. U., Baig, I., Takaijudin, H. B., & Zeshan, M. T. (2022). Assessment of Land Use Land Cover Changes and Future Predictions Using CA-ANN Simulation for Selangor, Malaysia. *Water (Switzerland),* 14(3). doi: 10.3390/w14030402

Banyumas Communication and Informatics Department. (2025). *Data and Information of Banyumas Regency 2025 (Vol. 9).* Banyumas Communication and Informatics Department.

Cumming, G. S., Buerkert, A., Hoffmann, E. M., Schlecht, E., Von Cramon-Taubadel, S., & Tscharntke, T. (2014). Implications of agricultural transitions and urbanization for ecosystem services. *Nature Publishing Group,* 515(7525), 50–57. doi: 10.1038/nature13945

Dawe, D. (2008). Can indonesia trust the world rice market?. *Bulletin of Indonesian Economic Studies,* 44(1), 115–132. doi: 10.1080/00074910802008053

Destiarni, R. P., Arifiyanti, N., & Jamil, A. S. (2024). An Almost Ideal Demand System approach in analysing demand for Indonesian imported rice. *BIO Web of Conferences*, 119. doi: 10.1051/bioconf/202411902014

Dumdumaya, C. E., & Cabrera, J. S. (2023). Determination of future land use changes using remote sensing imagery and artificial neural network algorithm: A case study of Davao City, Philippines. *Artificial Intelligence in Geosciences,* 4, 111–118. doi: 10.1016/j.aiig.2023.08.002

Entahabu, H. H., Minale, A. S., & Birhane, E. (2023). Modeling and Predicting Land Use/Land Cover Change Using the Land Change Modeler in the Suluh River Basin, Northern Highlands of Ethiopia. *Sustainability (Switzerland),* 15(10). doi: 10.3390/su15108202

Etim, N. M., Ivo, H. C., & Attah, A. U. (2024). Effects of Urban Growth on Peri-Urban Agriculture: A Review. *In International Journal of Research Publication and Reviews Journal homepage*, 5(5).

Fahri, A., Kolopaking, L. M., Dedi, D., & Hakim, B. (2014). The Rate of Paddy Field Conversion into Oil Palm Plantations, Its Determinant Factors, and Its Impact on Rice Production in Kampar Regency, Riau. *In Jurnal Pengkajian dan Pengembangan Teknologi Pertanian*, 17(1).

FAO. (1995). *Dimensions of Need: An Atlas of Food and Agriculture (T. Loftas, Ed.). Food and Agriculture Organization of United Nations.* Retrieved From https://ia800205.us.archive.org/

Gilbert, K. M., & Shi, Y. (2024). Urban Growth Monitoring and Prediction Using Remote Sensing Urban Monitoring Indices Approach and Integrating CA-Markov Model: A Case Study of Lagos City, Nigeria. *Sustainability (Switzerland),* 16(1). doi: 10.3390/su16010030

Jiang, L., Wu, S., Liu, Y., & Yang, C. (2021). Grain security assessment in Bangladesh based on supply-demand balance analysis. *PLoS ONE,* 16(5 May). doi: 10.1371/journal.pone.0252187

Kayitesi, N. M., Guzha, A. C., Tonini, M., & Mariethoz, G. (2024). Land use land cover change in the African Great Lakes Region: a spatial–temporal analysis and future predictions. *Environmental Monitoring and Assessment,* 196(9). doi: 10.1007/s10661-024-12986-4

Kou, J., Wang, J., Ding, J., & Ge, X. (2023). Spatial Simulation and Prediction of Land Use/Land Cover in the Transnational Ili-Balkhash Basin. *Remote Sensing,* 15(12). doi: 10.3390/rs15123059

Manjarrez-Domínguez, C., Uc-Campos, M. I., Esparza-Vela, M. E., Baray-Guerrero, M. D. R., Giner-Chávez, O., & Santellano-Estrada, E. (2023). Geospatial-Temporal Dynamics of Land Use in the Juárez Valley: Urbanization and Displacement of Agriculture. *Sustainability (Switzerland),* 15(11). doi: 10.3390/su15118499

Michael Lipton. (1976). *Why Poor People Stay Poor Urban Bias in World Development*. Australian National University Press.

Molla, M. B., Gelebo, G., & Girma, G. (2024). Urban expansion and agricultural land loss: a GIS-Based analysis and policy implications in Hawassa city, Ethiopia. *Frontiers in Environmental Science,* 12. doi: 10.3389/fenvs.2024.1499804

Munibah, K., Ambarwulan, W., Studi Pengelolaan Sumberdaya Alam dan Lingkungan, P., Pascasarjana, S., Sain dan Teknologi, F., Purwokerto, U., & Badan Riset dan Inovasi Nasional, P. (2024). Policy Directions Toward Rice Self-Sufficiency in Banyumas Regency, Central Java. Risalah Kebijakan Pertanian Dan Lingkungan. *IOP Conference Series: Earth and Environmental Science,* 11(1), 33–45.

Oort, P. A. J. Van, Saito, K., Tanaka, A., Amovin-Assagba, E., & ... (2015). *Assessment of rice self-sufficiency in 2025 in eight African countries. ... Food Security.* Retriefed From https://www.sciencedirect.com/science/article/pii/S2211912415000036

Owubah, C. (2024). *2024 Hunger Funding Gap Report.* Retriefed From https://www.actionagainsthunger.org/app/uploads/2024/01/Action-Against-Hunger-2024-Hunger-Funding-Gap-Report.pdf

Patunru, A. A., & Ilman, A. S. (2019). A Perspective on the ASEAN Economic Community Political Economy of Rice Policy in Indonesia: A Perspective on the ASEAN Economic Community. Center for Indonesian Policy Studies.

Park, M., Lee, J., & Won, J. (2024). Navigating Urban Sustainability: Urban Planning and the Predictive Analysis of Busan's Green Area Dynamics Using the CA-ANN Model. *Forests,* 15(10). doi: 10.3390/f15101681

Pratami, M., Susiloningtyas, D., & Supriatna. (2019). Modelling cellular automata for the development of settlement area Bengkulu City. *IOP Conference Series: Earth and Environmental Science,* 311(1). doi: 10.1088/1755-1315/311/1/012073

Purbiyanti, E., Yazid, M., & Januarti, I. (2017). *Paddy Field Conversion in Indonesia and Its Influence on the Government Rice Procurement Price (HPP) Policy. Jurnal Manajemen Dan Agribisnis.* Retrieved From https://doi.org/10.17358/jma.14.3.209. In Indonesia

Rizqi, B., & Manessa, M. D. M. (2025). Urban expansion and rice supply vulnerability: a modeling approach in proposed new autonomous region (PNAR) of Purwokerto, Indonesia. *IOP Conference Series: Earth and Environmental Science,* 1556(1). doi: 10.1088/1755-1315/1556/1/012095

Saleh, T. W., Lakitan, B., Budianta, D., Yamin, M., Sulastri, M. A., Cahya, G., & Huanza, M. (2025). The Impact of Rice Import Policy on Grain and Rice Prices in Indonesia (Case Study of Rice Import Data 2017-2023). *IOP Conference Series: Earth and Environmental Science,* 1482(1). doi: 10.1088/1755-1315/1482/1/012035

Setiadi, H., Dimyati, M., Rizqihandari, N., Restuti, R. C., Indratmoko, S., & Handayani, T. (2021). Paddy Field Conversion In Indonesia In A Contemporary Geographic Perspective: A Conceptual Overview Of Human-Nature Dialectics. *Jurnal Geografi,* 13(2), 195–210.

Setiartiti, L. (2021). Critical Point of View: The Challenges of Agricultural Sector on Governance and Food Security in Indonesia. *E3S Web of Conferences,* 232. doi: 10.1051/e3sconf/202123201034

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of the United States of America,* 109(40), 16083–16088. doi: 10.1073/pnas.1211658109

Simon, D. (2008). Urban environments: Issues on the peri-urban fringe. *Annual Review of Environment and Resources,* 33, 167–185. doi: 10.1146/annurev.environ.33.021407.093240

Siregar, R. K. (2018). *Analysis of the Factors Influencing Rice Imports in Indonesia [Institut Agama Islam Negeri Padasidimpuan].* Retrieved From https://etd.uinsyahada.ac.id/1424/1/14%20402%2000035.pdf. In Indonesia

Siti Syamsiar. (2013). *Rice Production and the Availability of Agricultural Land Resources to Strengthen Food Self-Sufficiency in the Special Region of Yogyakarta (DIY).* SEPA : Vol. 9, 183–189. In Indonesia

Skar, S. L. G., Pineda-Martos, R., Timpe, A., Pölling, B., Bohn, K., Külvik, M., Delgado, C., Pedras, C. M. G., Paço, T. A., Ćujic, M., Tzortzakis, N., Chrysargyris, A., Peticila, A., Alencikiene, G., Monsees, H., & Junge, R. (2020). Urban agriculture as a keystone contribution towards securing sustainable and healthy development for cities in the future. *Blue-Green Systems*, 2(1), 1–27. doi: 10.2166/bgs.2019.931

Statistics Indonesia. (2025). *Rice Imports by Major Country of Origin, 2017–2024*. Retrieved From https://www.bps.go.id

Sugandhi, N., Supriatna, S., Kusratmoko, E., & Rakuasa, H. (2022). Prediction of Land Cover Change in Sirimau District, Ambon City Using Cellular Automata–Markov Chain. *JPG (Jurnal Pendidikan Geografi*), 9(2). doi: 10.20527/jpg.v9i2.13880. In Indoneisa

Susanto, S., & Suhono, A. H. B. (2019). An analysis of irrigated paddy land contribution to maintain regional self sufficiency of food (rice) at Bantul regency of the special province of Yogyakarta. *IOP Conference Series: Earth and Environmental Science,* 355(1). doi: 10.1088/1755-1315/355/1/012016

Uddin, M. S., Mahalder, B., & Mahalder, D. (2023). Assessment of Land Use Land Cover Changes and Future Predictions Using CA-ANN Simulation for Gazipur City Corporation, Bangladesh. *Sustainability (Switzerland),* 15(16). doi: 10.3390/su151612329

Valero Medina, J. A., & Alzate Atehortúa, B. E. (2019). Comparison of maximum likelihood, support vector machines, and random forest techniques in satellite images classification. *Tecnura,* 23(59), 13–26. doi: 10.14483/22487638.14826

Wahyunto, & Widiastuti, F. (2014). The Role of Paddy Field on Food Resilience and National Food Self Sufficency. *Jurnal Sumberdaya Lahan Edisi Khusus,* 12, 17–30.

Woltjer, J. (2014). A Global Review on Peri-Urban Development and Planning. *Jurnal Perencanaan Wilayah Dan Kota,* 25(1), 1–16.