Prepublished Copy

NATURE ENVIRONMENT AND POLLUTION TECHNOLOGY

Article In Press

PEER-REVIEWED PREPUBLISHED MANUSCRIPT

This is a peer-reviewed prepublished version of the paper to be published in **Vol. 26, No. 1, March 2027.**

Cellular automata modelling of urban sprawl and microclimate conditions in Salatiga City

Wahid Akhsin Budi Nur Sidiq, Nana Kariada Tri Martuti, Muh Sholeh and Latri Setiyaningrum

RECEIVED
29 July 2026

CITE THIS ARTICLE
Sidiq, W.A.B.N., Martuti, N.K.T., Sholeh, M. and Setiyaningrum, L., 2027. Cellular automata modelling of urban sprawl and microclimate conditions in Salatiga City. *Nature Environment and Pollution Technology*, 26(1), D1970.

https://doi.org/10.46488/NEPT.2027.v26i01.D1970

EARLY-ACCESS STATEMENT

This manuscript, after peer review, is being released online in its original, unedited form to provide early access to its findings. Prior to final publication, it will undergo additional editing and formatting. Readers may note that, as an unedited version, the manuscript may have linguistic and other minor errors. The DOI will be active after the final publication of the paper.

PUBLICATION STATUS

PEER REVIEW	ONLINE VERSION	FINAL ISSUE
Completed	**Prepublished**	**March 2027**

© The Author(s) 2027. This article is Open Access under the Creative Commons Attribution 4.0 International License, allowing use, sharing, adaptation and reproduction with proper credit. Images or third-party material are covered by this licence unless otherwise noted. For uses beyond the licence, permission must be obtained from the copyright holder. Licence details: creativecommons.org/licenses/by/4.0/.

Type of Paper (Original Research)

Cellular Automata Modelling of Urban Sprawl and Microclimate Conditions in Salatiga City

Wahid Akhsin Budi Nur Sidiq[1], Nana Kariada Tri Martuti[2], Muh Sholeh[1], Latri Setiyaningrum[3]

[1] Department of Geography, Faculty of Social Sciences and Political Science, Universitas Negeri Semarang, Indonesia

[2] Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Indonesia

[3] The Asset and Business Optimization Agency, Universitas Negeri Semarang, Indonesia

† Corresponding author: Wahid Akhsin Budi Nur Sidiq; akhsin1987@mail.unnes.ac.id

ORCID IDs of Authors

Wahid Akhsin Budi Nur Sidiq: https://orcid.org/0000-0002-6057-5231

Nana Kariada Tri Martuti: https://orcid.org/0000-0002-3867-9026

Muh Sholeh: https://orcid.org/0009-0006-5160-149X

Latri Setiyaningrum: -

Abstract: Economic growth in the urban area of Salatiga is currently under pressure due to infrastructure expansion that is driving urban sprawl, which has the potential to cause long-term environmental degradation. The research methodology combines remote sensing with GIS, the random forest classification method, cellular automata, ground surface temperature, and statistical correlation tests, using Landsat time-series imagery as the data source. Land cover classification achieved accuracies above 80% for all methods. From 2012–2026, built-up land increased by 497.98 hectares, while vegetation decreased by 764.79 hectares, accompanied by a 250.07-hectare expansion of extreme surface temperature areas (>35°C). CA projections indicate potential built-up expansion to 2,623.54 hectares by 2042. Correlation analysis shows associations between land cover changes and LST ($r = +0.85$ for built-up land; $r = -0.90$ for vegetation), although these relationships do not imply direct causality due to the limitations of Landsat LST in representing urban microclimate conditions. This study is expected to support the achievement of Sustainable Development Goals (SDGs) 11 and 13.

Keywords: Cellular automata; Urban sprawl; Remote sensing; Microclimate

1. INTRODUCTION

The dynamics of global urbanization in recent years have led to an unprecedented spatial transformation, in which the physical expansion of modern cities is no longer merely linear but is spreading into peri-urban and rural areas through the phenomenon of uncontrolled urban sprawl (Huang et al., 2021)(Muter et al., 2025). Globally, the conversion of vegetated areas into built-up areas continues to increase, with an average growth rate of 1.5% to 2.3% per year, leading to massive loss of natural vegetation cover (Dibaba, 2023). Significant changes from natural

surfaces to large-scale impervious surfaces have disrupted the microclimate balance in several regions(Muter et al., 2025). This has led to an increase in Land Surface Temperature (LST), resulting in the Urban Heat Island (UHI) phenomenon worldwide, with local surface temperature increases ranging from 1.8°C to 4.5°C in urban areas (Fang et al., 2024). In general, haphazard urban expansion leads to a reduction in the landscape's evapotranspiration capacity (Gui et al., 2025). The leapfrog development pattern creates new thermal hotspots that disrupt the microclimate stability of urban buffer zones (Khan et al., 2024). To mitigate these adverse effects, spatially based predictive simulation modeling can be conducted, which is subsequently necessary for sustainable urban planning systems.

The Cellular Automata (CA) approach is currently recognized globally as the most adaptive and precise spatial tool for projecting the direction of dynamic built-up land growth. The main advantage of the CA model lies in its flexibility in integrating neighborhood rules, socioeconomic drivers, and physical environmental constraints simultaneously (Chakraborty et al., 2022)(Sidiq, Fariz et al., 2024). However, the main challenge in the current literature on land-use transition modeling is bridging the gap between the outputs of CA algorithms which generally produce only land-use classifications and continuous changes in the microclimate, such as LST values. Most previous studies treated temperature projections as a separate entity calculated using simple linear statistical methods after the land use simulation was completed (Liu et al., 2024). In fact, the interaction between the city's geometric structure, low albedo surface materials, and heat flux is nonlinear and involves mutual influence (Zhang et al., 2026). Therefore, an integrative approach is needed in which the transition probability matrix in cellular automata is combined with the surface thermal transfer function, so that future microclimate conditions can be projected simultaneously and dynamically based on evolving spatial growth scenarios (Anurogo et al., 2025).

Amid the development of these predictive methodologies, the phenomenon of massive urban physical expansion has now become a serious threat to secondary cities in developing countries, one of which is the city of Salatiga, Indonesia. Located within the strategic Semarang-Surakarta regional economic corridor, the city of Salatiga is experiencing extremely high anthropogenic pressure due to the agglomeration of residential areas, commercial corridors, and the expansion of higher education institutions (Buchori, 2021)(Imana et al., 2025). Empirical data confirms that physical growth in the city of Salatiga has converted more than 25% of productive agricultural land and green open spaces in a short period of time, transforming them into residential clusters and hard infrastructure (Mulya et al., 2026). These micro scale land use changes have been shown to correlate with

local climate warming anomalies, with satellite data analysis revealing an increase in the distribution of hot pixels (LST) that follow the patterns of the road network and new activity centers on the outskirts of Salatiga City (Buchori, 2021)(Heat et al., 2024). Geographically, the city of Salatiga has unique morphological characteristics because it is located on the slopes of Merbabu Mount, with undulating to hilly topography at an elevation of 450-800 meters above sea level. Historically, these mountainous characteristics have provided the advantage of a cool microclimate and relatively lower average temperatures compared to the surrounding coastal cities (Li dan Stringer, 2022). However, this sloping topography also causes urban sprawl to occur in a haphazard manner, concentrated in limited pockets of flat land or stretching along major transportation routes (Xi et al., 2025). When slope vegetation which functions as a mountain wind corridor is converted into artificial materials, topography induced thermal traps form, in which heat becomes trapped in built-up valleys due to impeded local air circulation. This results in the microclimate dynamics in Salatiga having a much higher degree of spatial complexity than those in lowland cities (Güller dan Toy, 2024)(Khan et al., 2024).

The urgency of this study stems from the long-term environmental impacts that the city of Salatiga will face if the trend of urban sprawl is allowed to continue unchecked. A surge in LST values an indicator of an uncontrolled microclimate directly reduces the community's thermal comfort, leading to wasteful domestic energy consumption due to reliance on mechanical air conditioners, and exacerbating the risk of degradation of the hilly urban ecosystem (Adesina et al., 2026). Conventional, static approaches to spatial planning have proven to be inadequate for mapping the nonlinear trajectory of urban development. Therefore, the development of science based predictive simulation models is essential as a mitigation tool for urban planners to formulate adaptive and sustainable regional spatial planning policies. Although a significant body of literature on the impact of urbanization on the microclimate has been published, most previous studies have tended to focus on large metropolitan areas with flat topography. The novelty of this study lies in the integration of Cellular Automata modeling with LST spatiotemporal analysis to evaluate the relationship between land cover changes and surface thermal conditions in hilly urban areas. This pixel-based approach allows for a more detailed identification of spatial patterns of urban expansion and variations in surface temperature compared to studies that focus solely on land-cover changes or general urban modeling. This integrative predictive approach successfully fills a significant research gap in studies of microclimate-related disasters in Indonesia, which have so far rarely linked dynamic physical growth simulations with precise projections of surface thermal temperatures (Nath dan Deka, 2025). Based on this research gap, this study aims to analyze the

historical spatiotemporal trends in urban development in the city of Salatiga, develop a predictive model for changes in built-up land cover using the Cellular Automata (CA) approach, and evaluate the relationship between changes in land cover resulting from urban expansion and microclimate variations represented by the Land Surface Temperature (LST) parameter. The results of this study are expected to provide new theoretical contributions to urban geography methodology and offer practical policy recommendations for the realization of a resilient green city. This study is expected to support the achievement of Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) and SDGs 13 (Climate Action).

2. MATERIALS AND METHODS

2.1. Research Sites

The city of Salatiga was chosen as the research site because of its strategic location along the main Semarang-Surakarta regional corridor and its unique geospatial characteristics. Located on the slopes of Mount Merbabu at an elevation of 450-800 meters above sea level, this secondary city which serves as an educational and commercial hub features varied topography; however, intense anthropogenic pressure has triggered aggressive urban sprawl, leading to the massive conversion of green open spaces. These undulating morphological characteristics, combined with this dynamic rate of physical growth, make the city of Salatiga an ideal spatial laboratory for testing the ability of cellular automata models to predict the direction of urban expansion and its impact on microclimate conditions. The following image shows the location of the research sites in Salatiga city (Figure 1).

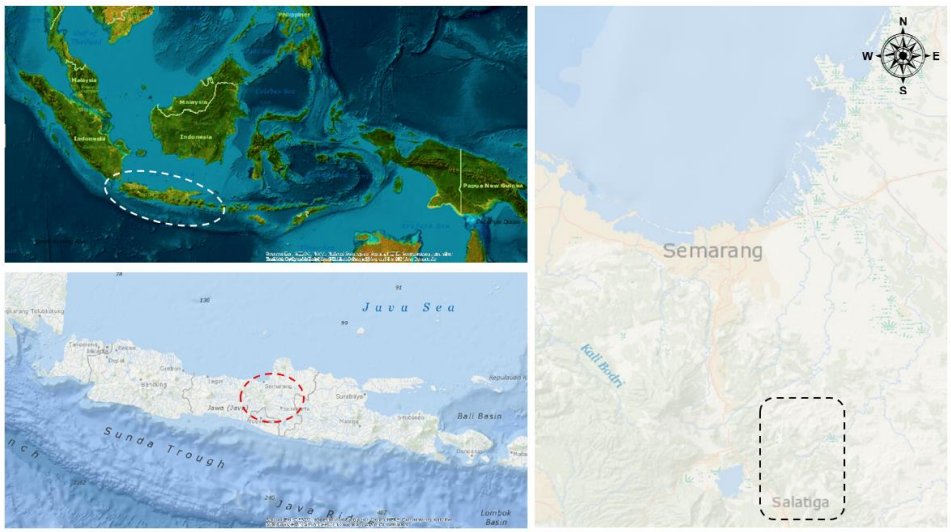


Fig 1. Research sites

2.2. Satelite Image Data Processing

The acquisition and preprocessing of satellite imagery data in this study were conducted entirely via cloud computing using the Google Earth Engine (GEE) platform. The primary data used were multitemporal United States Geological Survey (USGS) Landsat Level 2 Surface Reflectance (SR) products with a spatial resolution of 30 meters covering the city of Salatiga (Path 120/Row 65). This study used two generations of Landsat satellites for four observation periods:

- The year 2012: using Landsat 7 ETM+ data (blue, green, and red bands for land cover and the thermal band for microclimate).
- The year 2018, 2022, dan 2026: using Landsat 8 OLI/TIRS data (blue, green, and red bands for land cover and thermal band 10 for microclimate). Landsat 7 ETM+ and Landsat 8 OLI/TIRS data were aligned using Landsat Collection 2 products that have been geometrically, radiometrically, and atmospherically corrected. Both sensors have a spatial resolution of 30 m in the multispectral channel and a continuous observation program that enables temporal analysis. Differences in sensor characteristics are controlled through consistent preprocessing, so that the data can be used to compare changes in land cover and LST across time periods.

Landsat Collection 2 time-series data (2012, 2018, 2022, and 2026) were processed in Google Earth Engine (GEE) using cloud filtering (<10%), QA_PIXEL masking, and median compositing to reduce atmospheric effects. Differences between the Landsat 7 and Landsat 8 sensors were accounted for by using corrected Collection 2 products and selecting images from similar seasonal periods. The thermal band was resampled to 30 meters to match the multispectral resolution and the Cellular Automata grid. Land cover classification was performed using the Random Forest (RF) algorithm with proportional sampling per class and validated using an error matrix to ensure the reliability of the classification results. For microclimate modeling, this study is limited to the representation of surface thermal conditions using the Land Surface Temperature (LST) parameter. LST values were derived from Landsat satellite imagery using the thermal infrared band (Band 6/10), which was resampled following the Collection 2 Analysis Ready Data (ARD) standard. The thermal data were converted from digital numbers to temperature values using the provided scaling factor, followed by emissivity correction based on vegetation indices and conversion from Kelvin to degrees Celsius (°C). Therefore, the microclimate assessment in this study focuses on the spatial variation of surface temperature associated with land cover changes and does not directly represent other microclimate components, such as air temperature, relative humidity, wind speed, or solar radiation (Diaz et al., 2021).

2.3. Research Sample

Due to Landsat's 30-meter spatial resolution constraints, land cover classification was simplified into five main categories: built-up areas, open areas, vegetation, agricultural land, and water bodies. The machine learning algorithm utilized 80-100 samples per class, complying with the Badan Informasi Geospasial (BIG) recommendations for mapping projects with fewer than 12 classes. Furthermore, classification accuracy was evaluated using the Kappa index based on 120 reference pixels. The reference data were obtained from 30-meter-resolution Landsat

8 OLI imagery processed using Google Earth Engine (GEE). The imagery was used as reference data for cross validating the land cover classification results, considering the timing of acquisition and temporal variations in the imagery.

Table 1. Land cover class used in resarch sites

Land cover	Operational limitations
Built-up	all waterproof surfaces, including residential areas, office buildings, public facilities, industrial zones, and paved roads.
Open field	open field of land without vegetation cover, including vacant lots, open fields, and excavation sites.
Vegetation	the area is dominated by vegetation with high to moderate density, including forests, mixed plantations, and green open spaces.
Agriculture land	wetland and dryland areas for food crop cultivation, including paddy fields, dry fields, mixed crop fields, and horticultural farms.
Water body	all natural or artificial surface water bodies, including rivers, reservoirs, swamps, and large ponds.

Source: USGS classification, 2026

2.4. Driving Factors

Driving factors are crucial variables in developing a probabilistic model of built-up land transitions. Given the physiographic conditions of Salatiga City with its hilly topography and role as a secondary city serving as an educational and commercial hub this study identifies four main variables. These four factors were selected based on the following theoretical and empirical reasons:

Table 2. Driving factors for land cover change

Driving factors	Description
Road network	transportation accessibility is a key driver of a city's physical development, promoting a linear pattern of development.
Community activity center	as a driver of spatial growth due to the pull of economic agglomeration and socioeconomic activity.
Existing land cover	reflects the neighborhood effect in cellular automata logic, in which unbuilt cells located near existing built cells have a higher transition probability.
Topography	as a spatial constraint, where areas with steep slopes naturally reduce interest and increase construction costs.

Source: analysis, 2026

Spatial driving factors were processed in GIS and Google Earth Engine using data from the 1:25,000 Indonesian Topographic Map (road networks and activity centers), Landsat imagery (existing land use), and DEMNAS (topographic variables). To account for Salatiga's complex terrain, these factors were analyzed using the cost-distance method, which integrates physical terrain barriers and cumulative slope resistance to yield highly precise

urban sprawl probability projections. Cost-distance analysis is used to represent topographic barriers through a cost surface based on slope gradient. The cost values are normalized (0–1) and used as a control factor in a Cellular Automata model to simulate patterns of urban expansion (Xia, 2023)(Bachofer et al., 2026).

2.5. Land Cover Prediction

For land cover prediction, this study integrates Cellular Automata (CA) and Artificial Neural Networks (ANN) into a unified framework. Within this hybrid architecture, the ANN machine-learning algorithm autonomously extracts complex, non-linear relationships among physical and socioeconomic driving factors without requiring expert intervention (Alfia et al., 2025). By relying on neural network weights, the ANN objectively generates land cover transition probability matrices from historical land cover data (2012, 2018, 2022, and 2026) and spatial drivers. Modeling was conducted in two systematic stages. The first stage involved validating the 2026 Cellular Automata (CA) simulation results by comparing them with actual land cover conditions in 2026. Actual land cover data were obtained through direct satellite image classification on the Google Earth Engine (GEE) platform using the Random Forest (RF) algorithm. The level of agreement between the CA simulation results and actual land cover was then evaluated using a spatial accuracy test via ROC (Receiver Operating Characteristic Curve) to measure the model's ability to accurately represent land cover change patterns. The 2012–2018 period, which spans a six-year interval, was used as the basis for calibrating the rate of land-cover change, while projections were made using a four-year interval (2030–2042). The difference in time intervals was adjusted by normalizing the annual rates of change before they were used in the ANN–CA model for spatial simulation of urban expansion (Gui et al., 2025) (Hu dan Duan, 2026). Integrated within the MOLUSCE QGIS framework, this computational architecture produces highly accurate, ROC-validated projections that overcome traditional regression limitations, as illustrated in Figure 2.

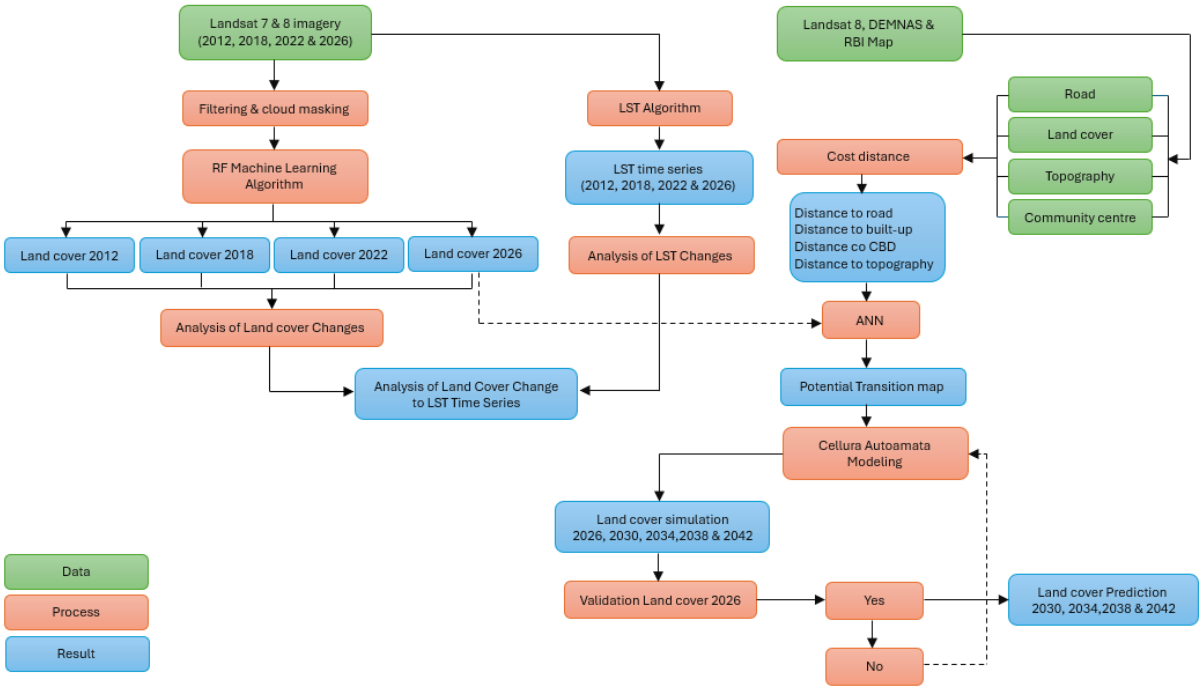


Fig 2. Flowchart Research

3. RESULTS AND DISCUSSION

3.1. Land Cover Existing Map Accuracy Test

The time series land cover maps for the study area underwent accuracy testing before being used for further analysis. This accuracy testing was conducted using two methods: Overall Accuracy (OA) and Kappa Accuracy (KA). The accuracy tests were performed on a series of land cover data sets processed using the Random Forest algorithm (2012, 2018, 2022, and 2026), where Random Forest was selected based on its ability and consistency to produce land use classifications that closely match on-the-ground conditions (Wang et al., 2022). The accuracy test results for all methods were mostly above 80%; however, the results of the 2026 land cover classification accuracy test yielded a Kappa value of 0.78. The accuracy for each class was as follows: built-up area 85.2%, open field 68.4%, vegetation 82.7%, agricultural land 70.1%, and water bodies 91.3%. Classification errors occurred primarily in the open field and agricultural land classes due to similarities in spectral response during the dry season. The homogeneity of color and pixel values in these two land cover classes made it difficult to select Regions of Interest (ROI), leading to anomalies in several land cover classes and resulting in low accuracy. ROI selection is a key indicator in land cover classification; the selected samples must accurately represent each land cover class and be free of mixed pixels (Waśniewski et al., 2023). If the classification results are still unsatisfactory as in the case of open field versus agricultural land the solution is to use visual interpretation. However, visual interpretation is less efficient at small to medium scale mapping, so some researchers still opt for digital classification. Table 3 shows the results of the time-series land cover accuracy test at the study site.

Table 3. Land Cover Time Series Mapping Accuracy Test Result

Machine learning	2012		2018		2022		2026	
	OA	Kappa	OA	Kappa	OA	Kappa	OA	Kappa
Random Forest (RF)	0.85	0.81	0.83	0.76	0.84	0.80	0.83	0.78

Source: Processing results, 2026

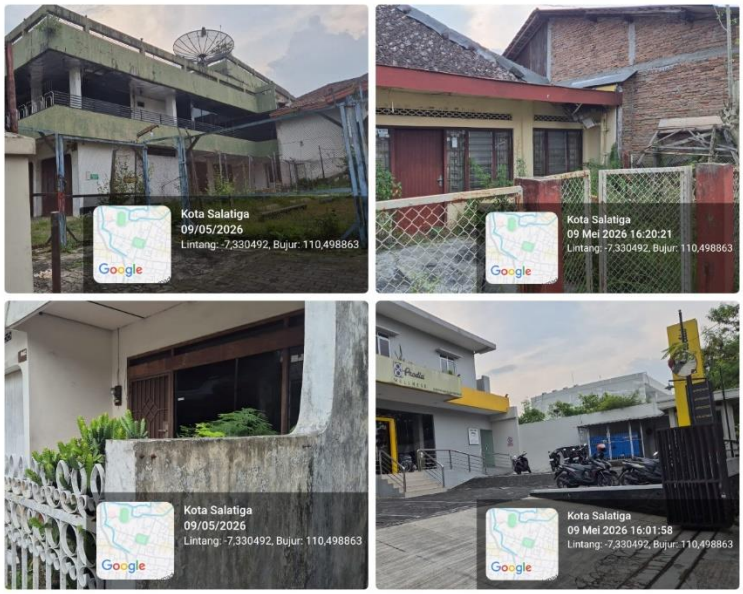


Fig 3. Built-up Eksisting in Research Sites

3.2. Land Cover Change

Based on the analysis of multitemporal satellite imagery, spatial dynamics in the city of Salatiga from 2012 to 2026 reveal a massive transformation in land cover, with built-up areas consistently increasing by approximately 497.98 hectares over the 2012-2026 period. The increase in the area of built-up areas indicates urban expansion in the study area; however, this alone is not sufficient to confirm the occurrence of urban sprawl without an analysis of spatial patterns. This development is linked to the dynamics of settlement growth, the economy, and infrastructure; therefore, spatial metrics are needed to evaluate the patterns of built-up area distribution. The expansion of built-up areas exerts significant ecological pressure, particularly on the existence of green open spaces in the study area (Sun et al., 2026), This phenomenon is evident in the reduction in the area of vegetation (forests and mixed plantations), which shrank by approximately 764.79 hectares from 2012 to mid 2026. However, an interesting phenomenon emerges from these dynamics: the area of agricultural land shows a linear upward trend, increasing from 555.94 hectares (2012) to 806.59 hectares (2026). This situation indicates a complex dual shift in land use, in which agricultural land in the city center is being converted into buildings, while much of the natural vegetation in the hilly areas is being converted into new agricultural land or dry field farming areas (Zhang et al., 2023). Furthermore, the area of open land cover fluctuates annually, ranging from approximately 25.11 to 60.13 hectares, and consists primarily of fields, yards, and land cleared for construction activities, whereas the area of water bodies remains stable each year at 0.19 hectares. This stability indicates that surface water features in the study area experienced minimal spatial changes during the observation period, suggesting that the dominant land

cover transitions were primarily associated with the conversion of vegetated and open areas into built-up surfaces rather than changes in aquatic environments.

From a biophysical perspective, this large-scale conversion of vegetated land into impervious surfaces is the primary driver of microclimate vulnerability in the city of Salatiga, where the loss of more than 700 hectares of vegetation cover over a 14 year period has directly reduced the landscape's cooling capacity through evapotranspiration. (Pohankov, 2024). Conversely, the massive increase in impervious surfaces such as asphalt, concrete, and building roofs significantly raises urban heat levels. It is this change in the biophysical structure of the surface that correlates with the region's microclimate, as urban sprawl mechanically creates new heat islands within the topography of the basins and hillsides of Salatiga City. (Alemayehu et al., 2026). Table 4 shows data on changes in land cover in the Salatiga city.

Table 4. Land Cover Time Series in Research Sites

No	Land cover	Area (hectares)			
		2012	**2018**	**2022**	**2026**
1	Bulit-up	1,258.97	1,424.81	1,643.58	1,756.95
2	Open field	42.39	60.13	25.11	58.55
3	Vegetation	3,820.63	3,591.04	3,337.03	3,055.84
4	Agricultural land	555.94	601.95	672.21	806.59
5	Water body	0.19	0.19	0.19	0.19
	Total	**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**

Source: analysis result, 2026

Based on the time-series land cover maps (Figures 3 and 4), Salatiga underwent massive urban expansion from the city center toward the outskirts—particularly to the north and south—between 2012 and 2026. This sprawl exhibits both ribbon development along transit corridors and leapfrog development forming isolated residential pockets (Hafiz et al., 2025)(Faiz et al., 2026). Consequently, uncontrolled built-up growth has fragmented and reduced dense northern vegetation, driving regional ecological degradation (Manna et al., 2025). Replacing natural cooling vegetation with heat-trapping built areas is deteriorating the urban microclimate; without decisive land-use planning interventions, Salatiga's outskirts risk losing their function as an environmental buffer (Narcizo et al., 2023). Figure 4 shows a time-series land cover map of the study site.

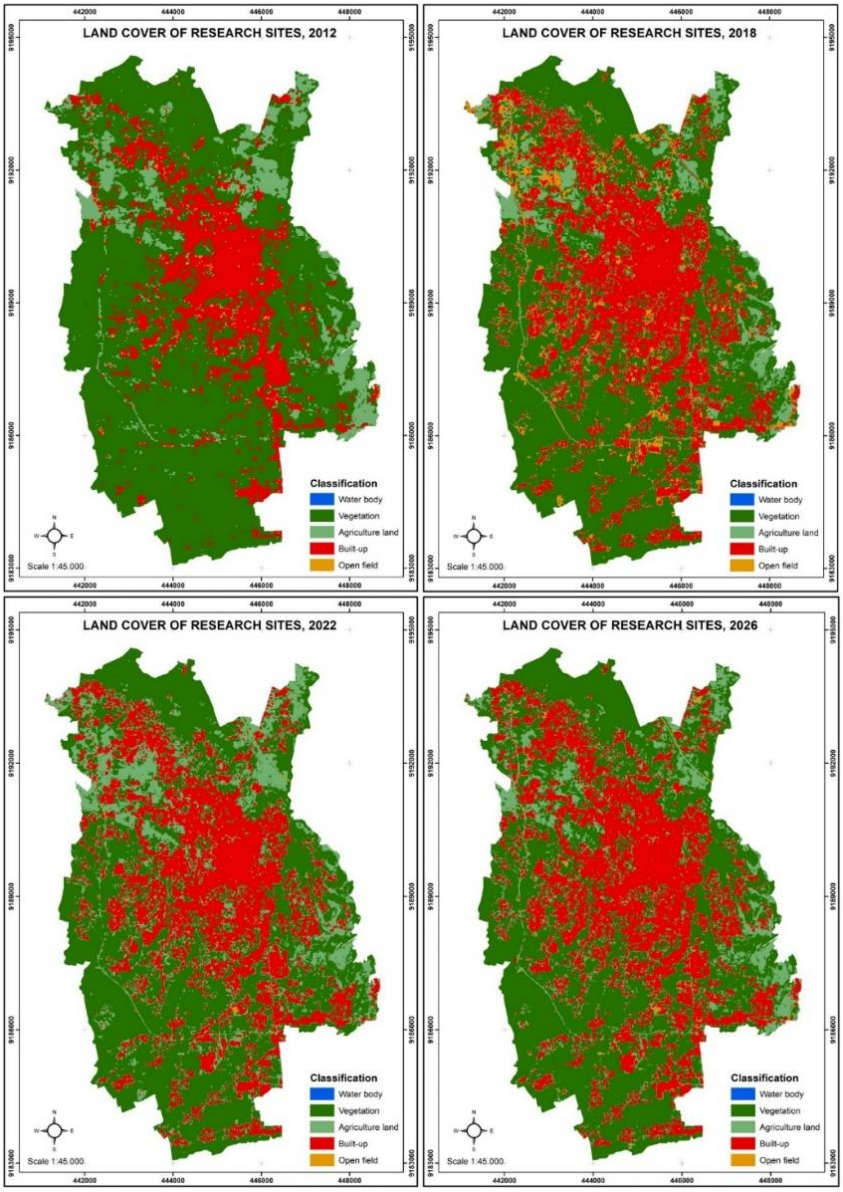


Fig 4. Land Cover Time Series in Research Sites

3.3. Microclimate Time Series

Analysis of the thermal bands of the Landsat time series imagery (2012, 2018, 2022, and 2026) reveals very clear changes in the microclimate of Salatiga City. The most significant change is a drastic increase in the area with high temperatures, where the area classified as hot (32.1-35°C) has continued to rise from 1,223.80 hectares (2012) to 1,818.87 hectares (2026). Furthermore, the area classified as "extremely hot" (>35°C) also increased from 746.58 hectares (2012) to 996.62 hectares (2026). One of the causes of this intensifying microclimate is the expansion of urban sprawl, which dominates the outskirts of Salatiga City (Panda dan Ray, 2026). Furthermore, Table 5 shows that the area within the comfortable temperature range (26.1-29°C) has shrunk significantly, with a decrease of

approximately 554.51 over the past 14 years. This reduction in the comfortable temperature zone is caused by the conversion of vegetated land into impervious built-up areas. These building materials absorb solar radiation more quickly and eliminate the landscape's natural ability to cool the environment through plant evaporation. (Javed et al., 2021)(Vujovic et al., 2021). Overall, this shift in trends from comfortable temperatures to extreme heat serves as strong evidence that urban sprawl exacerbates the microclimate and has the potential to create an Urban Heat Island. If the expansion of built-up areas continues unchecked without restrictions and the addition of green open spaces, the microclimate comfort of the residents of Salatiga will be increasingly threatened in the future. (Sidiq et al., 2024)(Hasyim et al., 2025). Table 5 shows the microclimate dynamics at research sites.

Table 5. Microclimate Time Series in Research Sites

No	Classification	Interval value	Area (hectares)			
			2012	2018	2022	2026
1	Cool temperature	< 26ºC	345,65	320,56	348,78	350,78
2	Comfortable temperature	26,1 – 29ºC	1,577.32	1,356.85	1,211.54	1,022.81
3	Critical temperature	29,1 – 32ºC	1,784.77	1,631.06	1,585.42	1,489.04
4	Hot temperature	32,1 - 35ºC	1,223.80	1,487.58	1,682.40	1,818.87
5	Very hot temperature	> 35ºC	746.58	882.07	849.98	996.62
	Total		**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**

Source: analysis results, 2026

Microclimate time-series spatial data (2012, 2018, 2022, and 2026) reveals that extremely high-temperature areas expanded from a concentrated city center outward in all directions particularly to the north and south. Consequently, heat distribution shifted from a localized cluster into a widespread issue affecting nearly the entire region (Gui et al., 2024)(Zhao et al., 2025). The spatial expansion of hot zones is directly linked to unchecked urban sprawl, as expanding suburban residential and commercial developments replace natural cooling vegetation with building materials that absorb and retain solar heat much longer (Ufaira et al., 2023)(Abedrabboh et al., 2025). These spatial conditions demonstrate that urban sprawl directly exacerbates the Urban Heat Island effect, as interconnected built-up areas form extensive heat-trapping surfaces. If current development trends continue, Salatiga risks losing its natural cooling capacity, creating an increasingly uncomfortable environment for future residents (Pradana et al., 2025). Figure 5 shows the microclimate time series at the research sites.

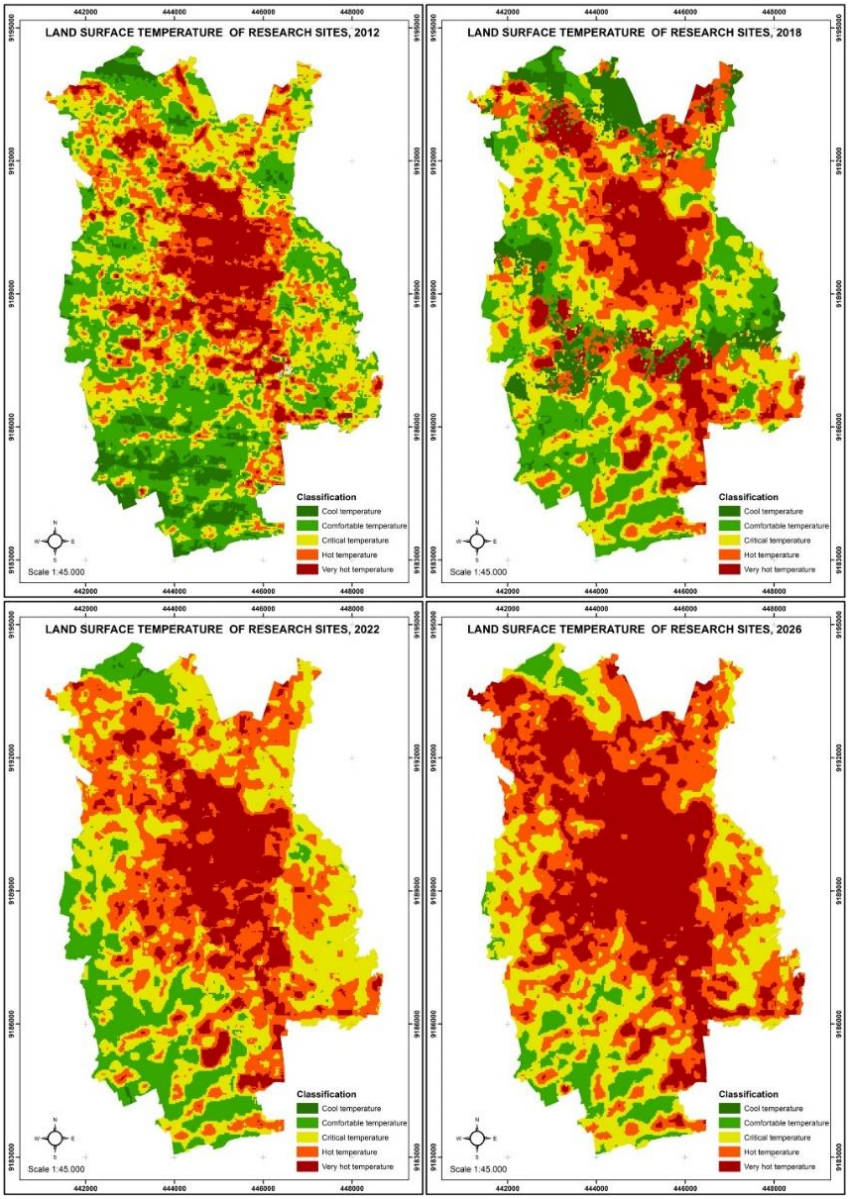


Fig 5. Microclimate from Land Surface Temperature Series in Research Sites

The 2026 Landsat LST results were validated by comparing them with MODIS LST data from the corresponding observation period. After the Landsat data were resampled to a spatial resolution of 1 km, the comparison results showed a strong correlation ($r = 0.86$) with an RMSE of 1.75°C, indicating consistency between the two satellite LST products. In addition, a comparison with BMKG air temperature data was conducted separately as an additional evaluation, given the differences in characteristics between surface temperature and atmospheric temperature. These validation results are used to assess the reliability of Landsat LST estimates, not as a direct representation of all microclimate components (Avdan dan Kaplan, 2016).

3.4. Land Cover Prediction

This study uses Cellular Automata (CA) to predict future land cover based on key spatial drivers: roads, activity centers, topography, and existing land use. It demonstrates that road networks trigger linear (ribbon) urban sprawl, whereas interactions between activity centers and topographic constraints drive leapfrog sprawl, creating isolated, sporadic residential pockets in previously vegetated outlying areas (Pradana et al., 2025). In the MOLUSCE environment, spatial modeling combines MLP-ANN and Cellular Automata (CA) with historical transition matrices to project urban sprawl. The MLP-ANN architecture uses 10 hidden layers, each consisting of a number of neurons, with the network weights optimized during the training process to learn the nonlinear relationships between spatial drivers and the probability of land-cover changes, with a 0.01 learning rate, 0.05 momentum, and up to 1,000 epochs. Then, CA applies a 3×3 Moore neighborhood filter to evaluate target pixels against their 8 neighbors and allocate land-cover changes, yielding dynamic, quantitative, and precise future projections (Figure 6).

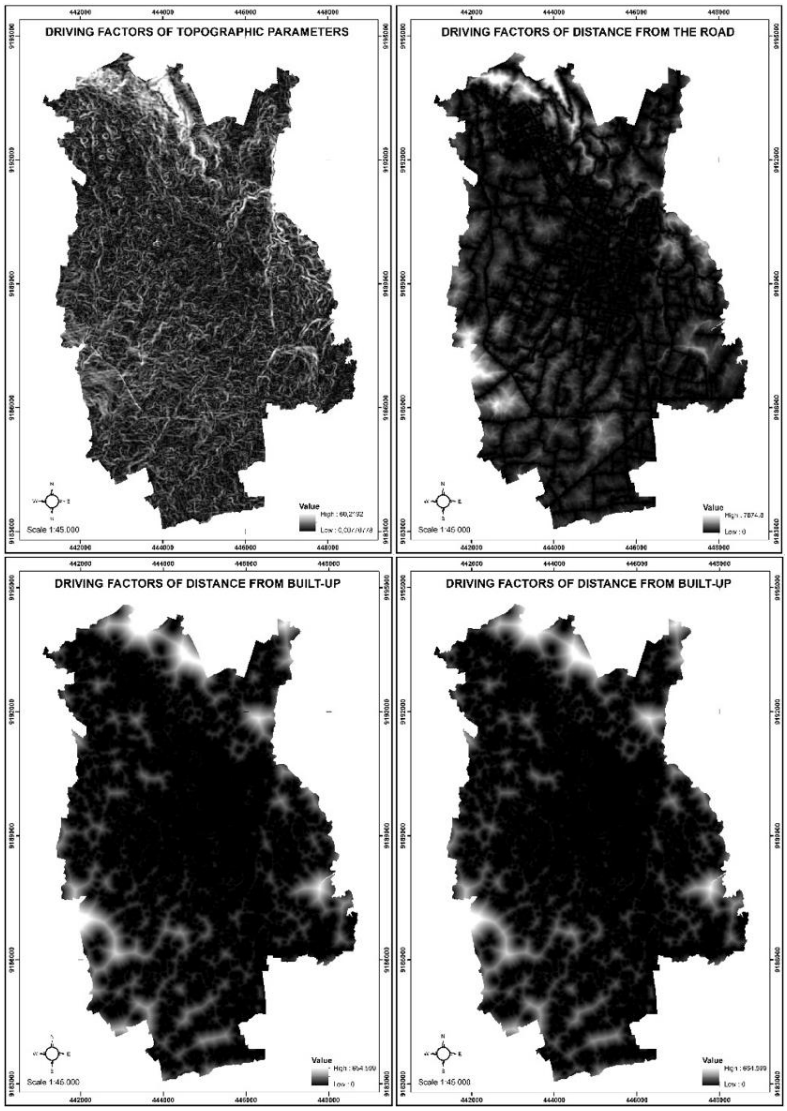


Fig 6. Driving Factor for Predicted Land Cover Change

Based on the land cover prediction results (Table 6), built-up land is projected to more than double, from 1,258.97 hectares (2012) to 2,623.54 hectares (2042). This sporadic expansion of built-up land directly converts vegetation areas, which are predicted to continue decreasing by approximately 1,422.62 hectares over the same period. This phenomenon of shrinkage indicates that the city is no longer growing densely toward its center but is instead expanding haphazardly, thereby damaging green open spaces in the outlying areas (Shawly, 2022). Uncontrolled suburban sprawl is clearly evident in agricultural land loss to built-up expansion, projected to reduce agricultural land to 620.76 hectares by 2042. Without strict land-use controls, continued sprawl will degrade environmental carrying capacity and escalate future microclimate temperatures (Rohman et al., 2024). Table 6 shows the results of land cover prediction at research sites.

Table 6. Land Cover Prediction in Research Sites

No	Land cover	Area (hectares)							
		2012	**2018**	**2022**	**2026**	**2030**	**2034**	**2038**	**2042**
1	Bulit-up	1,258.97	1,424.81	1,643.58	1,756.95	2,060.09	2,216.63	2,409.49	2,623.54
2	Open field	42.39	60.13	25.11	58.55	45,67	42,98	38,78	35,62
3	Vegetation	3,820.63	3,591.04	3,337.03	3,055.84	2.822,05	2,716.87	2,578.90	2,398.01
4	Agricultural land	555.94	601.95	672.21	806.59	750.12	701.45	650.76	620.76
5	Water body	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
	Total	**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**	**5,678.12**

Source: analysis results, 2026

The 2030–2042 land cover prediction map shows built-up areas increasingly dominating Salatiga, expanding from the city center toward the outskirts through edge-expansion and ribbon development. In this process, physical growth spreads outward along major road networks, progressively encroaching upon and converting adjacent vegetation (Ansari, 2026). Beyond central expansion, projected built-up growth highlights leapfrog urban sprawl emerging far from main urban centers, particularly in the north and south. This random, fragmented development is environmentally detrimental, as establishing new residential areas within vacant land directly fragments vegetation and agricultural land into small, isolated patches (Glockmann dan Rybski, 2022). Land cover projections through 2042 indicate that combined linear and leapfrog sprawl will transform Salatiga by interconnecting built-up areas and eliminating most suburban green open spaces. Without strict land-use restrictions, this unregulated sprawl will strip the city of its natural buffer function, ultimately triggering severe environmental issues such as clean water shortages and increased urban heat (Enock dan Isaac, 2025). Figure 7 shows the spatial distribution of land cover as predicted using cellular automata modeling.

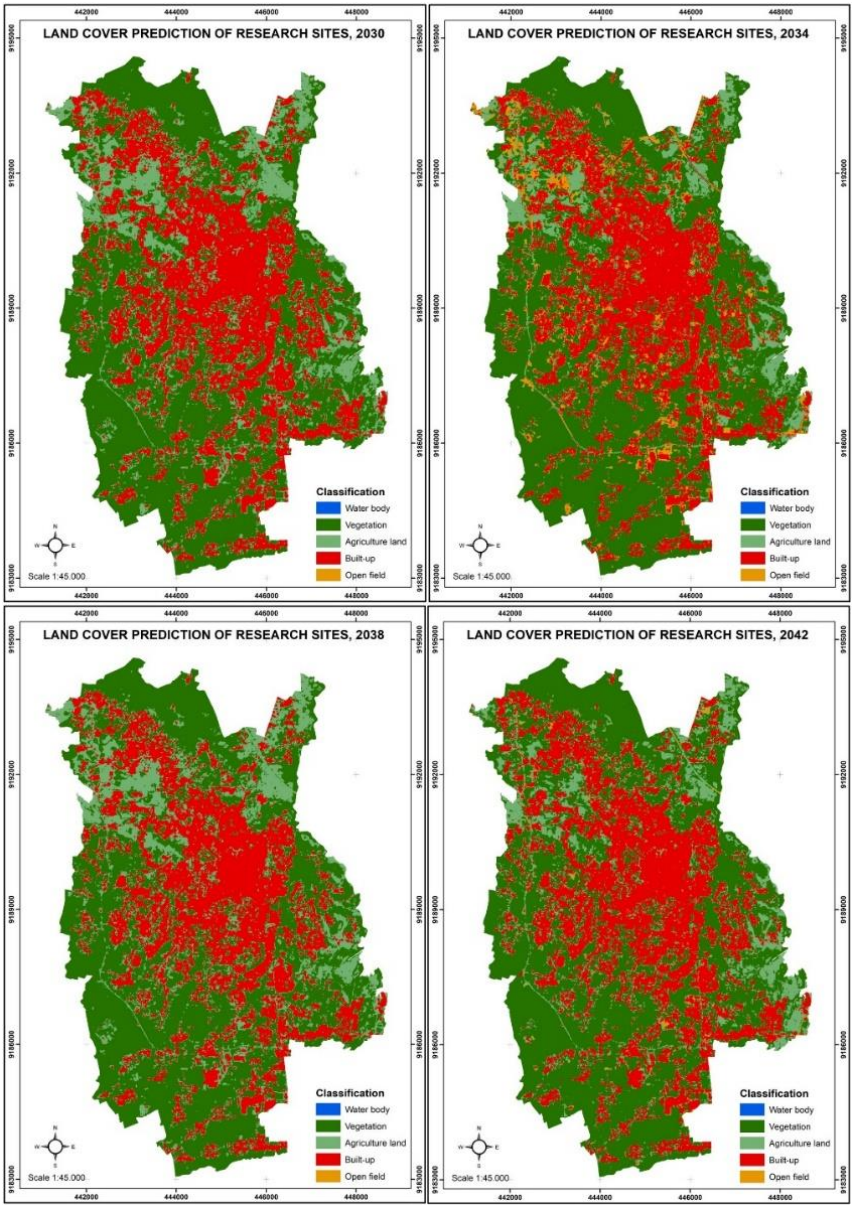


Fig 7. Land Cover Prediction Time Series in Research Sites

Next, to assess the accuracy of the land cover prediction map, an accuracy test was conducted comparing the 2026 land cover map generated by random forest classification with the 2026 CA prediction map using the Relative Operating Characteristic (ROC) method, which is ideal for validating the output of the ANN stage (Transition Potential Map) before proceeding to the Cellular Automata (CA) stage The results of the accuracy test using the ROC method showed a value of 0.76, which falls within the "acceptable" category and indicates that the Cellular Automata (CA)-based land cover prediction model has good predictive capability. Although it has not yet reached a very strong level, this value is still scientifically adequate for use in land cover change analysis (Tesfaye, 2025).

3.5. Correlation on Land Cover Changes to Microclimate

Driven by population and economic growth, urban sprawl in Salatiga converts peripheral natural landscapes into built-up land, severely impacting the local microclimate. Replacing natural surfaces with man-made materials disrupts thermal balance, creating an increasingly hot and uncomfortable living environment (Rahman dan Mark, 2025)(Loan et al., 2026). Land cover dynamics from 2012 to 2026 (Figure 6) highlight the impact of urban sprawl in Salatiga: driven by housing and road infrastructure demand, built-up land increased consistently by 500 hectares, while green open spaces drastically shrank from 3,800 to 3,050 hectares. This loss severely harms ecosystem balance by diminishing the natural cooling provided by vegetation through evapotranspiration. (Yin, 2024)(Chen et al., 2025).

Vegetation loss coupled with built-up expansion directly disrupts the urban microclimate. As illustrated in Figure 6 (orange line: "very hot" area), urban sprawl and reduced vegetation strongly correlate with a ~250.07-hectare increase in extreme-temperature areas between 2012 and 2026. This shift occurs because man-made surfaces absorb solar radiation far longer than grassy areas, driving the Urban Heat Island effect and elevating air temperatures in Salatiga (Kilinc et al., 2025). Despite a brief 2022 drop to 850 hectares caused by weather anomalies like a longer rainy season, the extreme heat area is projected to reach 1,000 hectares by 2026. This post-2022 rebound demonstrates that vegetation loss from urban development exerts a far more dominant and permanent long-term impact on the microclimate than temporary weather fluctuations. (Belkhiri dan Onescu, 2026). Overall, urban sprawl has proven to be the primary cause of the decline in thermal comfort in the city of Salatiga. Figure 8 shows trends in land-cover changes in areas with extremely high temperatures at the research sites.

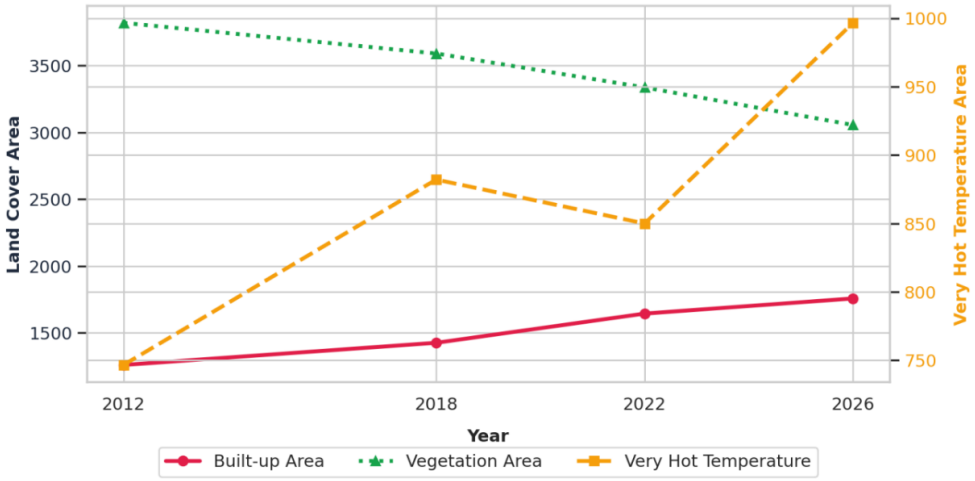


Fig 8. Trends of Built-up Change and Vegetation in Areas with Extremely High Temperatures

Analysis of the statistical scatter plot (Figure 7) reveals a relationship between changes in land cover and the dynamics of urban surface temperature. A strong positive correlation (r = +0.85) between increases in built-up areas and regions with extreme temperatures indicates that the expansion of built-up land is associated with rising surface temperatures, consistent with the characteristics of urban materials that can absorb and store heat (Ainulmila et al., 2025) (Filonchyk et al., 2024). Conversely, a strong negative correlation between vegetation area and zones of extreme temperatures (r = −0.90) suggests that the presence of vegetation is associated with a reduction in surface heat intensity through its role in regulating the microclimate (Kafy et al., 2022) (Arriaga-osuna et al., 2026). However, these correlation results must be interpreted with caution because they are based on only four observation periods (2012, 2018, 2022, and 2026), thus indicating an associative relationship rather than proving a direct cause-and-effect relationship. Figure 9 shows the correlation between changes in land cover and areas with extremely high temperatures.

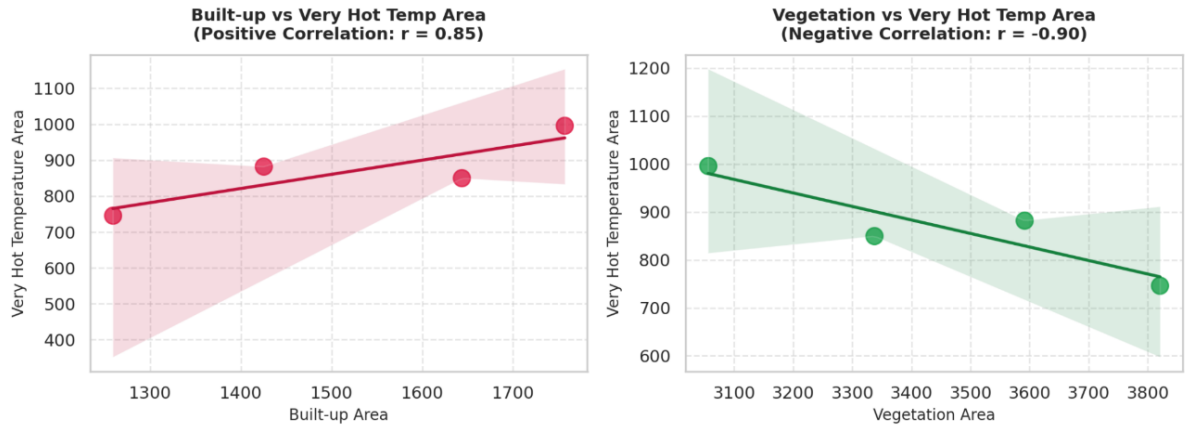


Fig 9. Correlation Between Built-up and Vegetation to Areas of Extremely High Temperatures

These two statistical correlations warn urban planners and policymakers that expanding physical infrastructure alone directly threatens microenvironmental sustainability and is no longer viable. Urban planning must immediately pivot toward green infrastructure implementing mandatory green space in new residential developments, green roofs, and eco-friendly road materials to break the Urban Heat Island cycle (Patel et al., 2023)(Khalili et al., 2024). Ignoring extreme heat warnings will directly harm the public by lowering quality of life, triggering health risks, and driving up electricity consumption from air conditioning. Balancing built-up and green areas is a vital future investment, making firm government control over urban sprawl essential to ensure cities remain comfortable, resilient, and livable for future generations (Umeike et al., 2025)(Pribadi, 2026).

4. CONCLUSIONS

Based on the research findings, it can be concluded that the study area underwent massive spatial transformation due to the phenomenon of urban sprawl throughout the 2012-2026 period and projections through 2042. The city's physical growth influenced by factors such as the road network, community activity centers, topography, and existing built-up areas developed through patterns of ribbon development and leapfrog development. The impact of this phenomenon is a massive increase in built-up land, which is converting areas of natural vegetation in the outskirts. This uncontrolled change in land cover disrupts the city's microclimate balance and has the potential to create an urban heat island (2012-2026) . This relationship is reinforced by statistical analysis showing a very strong positive correlation between the expansion of built-up land and the spread of extremely hot temperature zones ($r = +0.85$), as well as a nearly perfect inverse relationship resulting from the shrinking of vegetation areas that act as natural environmental coolers ($r = -0.90$). Although this study successfully provided clear information on land cover change trends, there are fundamental limitations related to the use of Landsat time-series satellite imagery, as the thermal band in these images has too low a spatial resolution to extract microclimate data at the intra-urban level. Given the current limited availability of free thermal data from natural resource satellites, future research is strongly recommended to supplement this modeling with direct in field temperature measurements. Integrating these field data can validate remote sensing results against actual conditions at the micro-scale, thereby enabling the formulation of far more accurate urban microclimate mitigation strategies for policymakers in the city of Salatiga. This study is expected to support the achievement of Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

Author Contributions: Conceptualization, W.A.B.N.S. and N.K.T; methodology, W.A.B.N.S. and M.S; validation, W.A.B.N.S and M.S.; formal analysis, N.K.T and L.S; investigation, N.K.T; data curation, W.A.B.N.S; writing original draft preparation, W.A.B.N.S and L.S; writing review and editing, W.A.B.N.S and L.S.; supervision, N.K.T and M.S; project administration, L.S; funding acquisition, W.A.B.N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universitas Negeri Semarang through the Institute for Research and Community Service (LP2M), under the 2026 DPA LP2M Universitas Negeri Semarang funding scheme, based on Decree/Announcement No. 76.8.4/UN37/PPK.11/2026

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to express their sincere gratitude to the Institute for Research and Community Service (LPPM) Universitas Negeri Semarang for providing research funding support through the DPA LPPM Universitas Negeri Semarang under the Basic Research Scheme (Skema Penelitian Dasar). This research was funded by the research grant with contract number 76.8.4/UN37/PPK.11/2026 dated 08 April 2026.

Conflicts of Interest: The authors declare no conflicts of interest.

REFERENCES

Abedrabboh, O., Alfarra, M.R., Al-ansari, T., Fountoukis, C., 2025. Enhancing human thermal comfort in hot arid cities : A systematic review of urban heat island observations and mitigation strategies. Build. Environ. 283, 113398. https://doi.org/10.1016/j.buildenv.2025.113398

Adesina, E.A., Ajayi, O.G., Odumosu, J.O., Taiwo, E.O., 2026. Dynamic suitability-weighted CA-Markov model for projecting urban growth and thermal impacts : a case study of Abuja. Nov. Geod. 6, 1–22.

Ainulmila, A., Tiana, S., Mumtaz, K.N., Azhari, D.S.F., Ibrahim, F., 2025. Correlation Analysis of Land Surface Temperature (LST) and Vegetation Density Using Landsat 8 and 5 Imagery in Purwakarta Regency. Int. Conf. Data Sci. Off. Stat. 110–125. https://doi.org/DOI:10.34123/icdsos.v2025i1.528

Alemayehu, T., Haimanote, W., Moged, T., Jothimani, M., Tadese, A., 2026. Spatiotemporal assessment of urban expansion and its impact on land surface temperature in Adama City , Ethiopia. City Environ. Interact. 31, 100414. https://doi.org/10.1016/j.cacint.2026.100414

Alfia, L., Nugroho, F., Arif, Y., 2025. Comparative Analysis of Artificial Neural Networks, Linear Regression, Random Forest, and Support Vector Machine for Predicting Poverty Levels in Indonesia. Int. J. Adv. Data Inf. Syst. 6, 789–800. https://doi.org/10.59395/ijadis.v6i3.1467

Ansari, N., 2026. Sustainable urban expansion and land use dynamics in North Bengal ' s urban and peri-urban areas : A trajectory-based forecasting approach. J. Urban Manag. 15, 1117–1141. https://doi.org/10.1016/j.jum.2025.12.009

Anurogo, W., Putra, A., Tarigan, A., Seftyarizki, D., Prihantarto, W.J., Woo, J., Catarino, S., Arora, A.S., Gohaud, E., Meller, B., 2025. Cellular Automata – Artificial Neural Network Approach to Dynamically Model Past and Future Surface Temperature Changes : A Case of a Rapidly Urbanizing Island Area , Indonesia. Land 1–20.

Arriaga-osuna, M.F., Martínez-torres, K.E., Gonzalez-trevizo, M.E., Esparza-lopez, C.J., González-lópez, B.Y., 2026. Microclimatic Simulation Tools to Evaluate Urban Heat Mitigation : Vegetation and Urban Surface Strategies for Sustainable Environments. Climate 14, 1–30. https://doi.org/https://doi.org/10.3390/cli14060132

Avdan, U., Kaplan, G., 2016. Algorithm for Automated Mapping of Land Surface Temperature Using LANDSAT 8 Satellite Data. J. Sensors 2016, 1–8. https://doi.org/10.1155/2016/1480307

Bachofer, F., Wang, Z., Huth, J., Eisfelder, C., Reimuth, A., Kuenzer, C., 2026. Urban growth prediction along Shared Socioeconomic Pathways (SSPs) for future flood exposure risk assessment : a cross - continental analysis of coastal cities. Anthr. Coasts 9, 1–28. https://doi.org/https://doi.org/10.1007/s44218-025-00109-6

Belkhiri, K., Onescu, I., 2026. Integrating Sustainability into Urban Planning : A Systematic Review of Policies Addressing Hazard Risks and Climate Change. Sustainability 18, 1–35. https://doi.org/https://doi.org/10.3390/su18042068

Buchori, D.D.D. and I., 2021. Assessment of Rapid Urban Development Impact for a Small-Sized Transit City Using Remote Sensing : A Case Study of Salatiga , Indonesia Assessment of Rapid Urban Development Impact for a Small- Sized Transit City Using Remote Sensing : A Case Study of Sal. IOP Conf. Ser. Earth Environ. Sci. Pap. https://doi.org/10.1088/1755-1315/887/1/012009

Chakraborty, A., Sikder, S., Omrani, H., 2022. Cellular Automata in Modeling and Predicting Urban Densification : Revisiting the Literature since 1971. Land.

Chen, H., Liu, B., Deng, Y., Zhao, H., Chang, C., Xue, H., Dong, X., Zhang, H., Wang, S., 2025. Urbanization reduces evapotranspiration and alters its components across 20 global urban forests. Earth Crit. Zo. 2, 100045. https://doi.org/10.1016/j.ecz.2025.100045

Diaz, L.R., Santos, D.C., Savannah, T., Kaiser, E.A., Beatriz, S., Rolim, A., 2021. Atmospheric Correction of Thermal Infrared Landsat Images Using High-Resolution Vertical Profiles Simulated by. Enviromental Sci. Proc. 8. https://doi.org/https://doi.org/10.3390/ecas2021-10351

Dibaba, W.T., 2023. Urbanization-induced land use/land cover change and its impact on surface temperature and heat fluxes over two major cities in Western Ethiopia. Environ. Monit. Assess. 195, 1–20.

Enock, A., Isaac, A., 2025. Assessing the impacts of urban sprawl and encroachment on Muni-Pomadze Lagoon ecosystem at Winneba , Ghana. SN Soc. Sci. 5. https://doi.org/https://doi.org/10.1007/s43545-025-01092-y

Faiz, M., Faridi, R.A., Falah, F., Hasher, B., Boltižiar, M., 2026. Quantitative Assessment of Urban Sprawl Dynamics in Moradabad City Using Built-Up Expansion Index and Shannon ' s Entropy (1994 – 2024). Land 15, 1–42. https://doi.org/https://doi.org/10.3390/land15071212

Fang, Q., Liu, C., Ren, Z., Fu, Y., Fan, H., Wang, Y., Yu, Z., 2024. Spatiotemporal Analysis of Surface Urban Heat Island Dynamics in Central Yunnan City Cluster. Sustainability.

Filonchyk, M., Peterson, M.P., Zhang, L., Hurynovich, V., He, Y., 2024. Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. Sci. Total Environ. 935, 173359. https://doi.org/https://doi.org/10.1016/j.scitotenv.2024.173359

Glockmann, M., Rybski, D., 2022. Quantitative evidence for leapfrogging in urban growth. Urban Anal. City Sci. 49. https://doi.org/10.1177/2399808321998713

Gui, B., Bhardwaj, A., Sam, L., 2025. Artificial Intelligence in Geosciences Cellular automata models for simulation and prediction of urban land use change : Development and prospects. Artif. Intell. Geosci. 6, 100142. https://doi.org/10.1016/j.aiig.2025.100142

Gui, B., Bhardwaj, A., Sam, L., 2024. Revealing the evolution of spatiotemporal patterns of urban expansion using mathematical modelling and emerging hotspot analysis. J. Environ. Manage. 364, 121477. https://doi.org/10.1016/j.jenvman.2024.121477

Güller, C., Toy, S., 2024. The Impacts of Urban Morphology on Urban Heat Islands in Housing Areas : The Case of Erzurum , Turkey. Sustainability.

Hafiz, A., Usman, F., Hidayat, A.R., Zakiyah, D., 2025. Spatiotemporal Dynamics of Urban Sprawl Types in the Peri-Urban Area of Malang Municipality, Indonesia. Urban Sci. 9, 313. https://doi.org/10.3390/urbansci9080313

Hasyim, A.W., Sukojo, B.M., Anggraini, I.A., Fatahillah, E.R., 2025. International Journal of Sustainable Development and Planning Urban Heat Island Effect and Sustainable Planning : Analysis of Land Surface Temperature and Vegetation in Malang City. Int. J. Sustain. Dev. Plan. 20, 683–697. https://doi.org/https://doi.org/10.18280/ijsdp.200218

Heat, N., Island, C., Qi, L., Hu, Y., Bu, R., Li, B., Gao, Y., Li, C., 2024. Evaluation of the Thermal Environment Based on the Urban. Land.

Hu, L., Duan, X., 2026. Application and Assessment of a CA-ANN Model for Land Use Change Simulation and Multi-Temporal Prediction in Guiyang City , China. Sustainability 15, 1–24. https://doi.org/https://doi.org/10.3390/su18031518

Huang, Q., Zhang, H., Vliet, J. Van, Ren, Q., 2021. Patterns and Distributions of Urban Expansion in Global Watersheds Earth ' s Future. Adv. Earth Sp. Sci. 1–16. https://doi.org/10.1029/2021EF002062

Imana, R., Emma, A., Okta, D., 2025. Regional Sustainability Analysis of environmental protection priority zones and their impacts on urban planning in small- and medium-sized cities of Indonesia. Reg. Sustain. 6, 100211. https://doi.org/10.1016/j.regsus.2025.100211

Javed, Z.H., Bin, H., Awan, H., 2021. Influence of Urban Sprawl on Microclimate of. Land 10. https://doi.org/https://doi.org/10.3390/land10020095

Kafy, A.- Al, Faisal, A.-A.-, Al Rakib, A., Fattah, M.A., Rahaman, Z.A., Sattar, G.S., 2022. Impact of vegetation cover loss on surface temperature and carbon emission in a fastest-growing city, Cumilla, Bangladesh. Build. Environ. 208, 108573. https://doi.org/https://doi.org/10.1016/j.buildenv.2021.108573

Khalili, S., Kumar, P., Jones, L., 2024. Heliyon Evaluating the benefits of urban green infrastructure : Methods , indicators ,

and gaps. Heliyon 10, e38446. https://doi.org/10.1016/j.heliyon.2024.e38446

Khan, M., Qasim, M., Ahmad, A., Ahmad, A., 2024. Heliyon Predicting land use dynamics , surface temperature and urban thermal field variance index in mild cold climate urban area of Pakistan. Heliyon 10, e38787. https://doi.org/10.1016/j.heliyon.2024.e38787

Kilinc, M., Aydin, C., Aydin, G.E., Balci, D., 2025. Exploring the Urban Heat Island Effect : A Bibliometric and Topic Modeling Analysis. Sustainability 15, 1–26. https://doi.org/https://doi.org/10.3390/su17178072

Li, X., Stringer, L.C., 2022. The Impacts of Urbanisation and Climate Change on the Urban Thermal Environment in Africa. Climate 1–21.

Liu, H., Zhou, Z., Wen, Q., Chen, J., Kojima, S., 2024. Spatiotemporal Land Use / Land Cover Changes and Impact on Urban Thermal Environments : Analyzing Cool Island Intensity Variations. Sustainability.

Loan, D.T., Jian, G., Thi, Ngo, Guohua, Z., Thi, Nguyen, Ha, T., 2026. land-use / land-cover changes and land surface temperature in Ha Noi city , Viet Nam. Nat. Hazards 122, 1–36. https://doi.org/https://doi.org/10.1007/s11069-025-07763-6

Manna, H., Pramanik, M., Pal, R., Sarkar, S., 2025. Environmental and Sustainability Indicators Land use land cover change and habitat quality degradation in the tropical megacity of Bangkok : An integrated CA – Markov and InVEST modeling. Environ. Sustain. Indic. 28, 101036. https://doi.org/10.1016/j.indic.2025.101036

Mulya, S.P., Rohmah, D.F., Rustiadi, E., 2026. Rural – Urban Transition and Control of Agricultural Land Change in Greater Bandung Area , Indonesia. Sustainability 1–25.

Muter, S.A., Tawfeek, Y.Q., Al-jiboori, M.H., Abd, J.S., Rukabie, A., 2025. Assessing Climate Sensitivity to Urban Land-Use Changes in Iraq. Nat. Environ. Pollut. Technol. 24. https://doi.org/https://doi.org/10.46488/NEPT.2025.v24i03.D1752

Narcizo, G., Ma, D.L., Fonseca, A., Campo, J., 2023. Urban growth and loss of green spaces in the metropolitan areas of São Paulo and Mexico City : effects of land - cover changes on climate and water flow regulation. Urban Ecosyst. 26, 1739–1752. https://doi.org/10.1007/s11252-023-01394-0

Nath, R., Deka, S., 2025. Environmental and Sustainability Indicators Urbanization and its impact on microclimate dynamics and thermal comfort : A predictive assessment of Guwahati ' s evolving landscape. Environ. Sustain. Indic. 28, 100964. https://doi.org/10.1016/j.indic.2025.100964

Panda, S., Ray, S.S., 2026. Analyzing urban sprawl in medium sized cities - Case of Bhubaneswar city, India. Glob. Challenges Reg. Sci. 100025. https://doi.org/10.1016/j.gcrs.2026.100025

Patel, S., Indraganti, M., Jawarneh, R., 2023. A comprehensive systematic review: Impact of Land Use/ Land Cover (LULC) on Land Surface Temperatures (LST) and outdoor thermal comfort. Build. Environ. 249, 111130. https://doi.org/10.1016/j.buildenv.2023.111130

Pohankov, T., 2024. Assessing the Cooling Potential of Vegetation in a Central European Rural Landscape : A Local Study. Land 13. https://doi.org/https://doi.org/10.3390/land13101685

Pradana, R.P., Bhanage, V., Fajary, F.R., Hussainzada, W., Badriana, M.R., Lee, H.S., Kubota, T., Nimiya, H., Gede, I.D., Putra, A., 2025. Assessing Green Strategies for Urban Cooling in the Development of Nusantara Capital City , Indonesia. Climate 15, 1–22. https://doi.org/https://doi.org/10.3390/cli13020030

Pribadi, D.O., 2026. Greening cities amidst urban sprawl and fragmented governance in the Global South mega-urban regions. Front. Sustain. Cities 1–5. https://doi.org/10.3389/frsc.2026.1844228

Rahman, R., Mark, B.G., 2025. Geospatial Analysis of Urban Warming : A Remote Sensing and GIS-Based Investigation of Winter Land Surface Temperature and Biophysical Composition in Rajshahi City , Bangladesh. Sustainability 17, 1–32. https://doi.org/https://doi.org/10.3390/ su17115107

Rohman, F., Soo, H., Kubota, T., Bhanage, V., Putra, R., Nimiya, H., Gede, I.D., Putra, A., 2024. Heliyon Comprehensive

spatiotemporal evaluation of urban growth , surface urban heat island , and urban thermal conditions on Java island of Indonesia and implications for urban planning. Heliyon 10, e33708. https://doi.org/10.1016/j.heliyon.2024.e33708

Shawly, H., 2022. Evaluating Compact City Model Implementation as a Sustainable Urban Development Tool to Control Urban Sprawl in the City of Jeddah. Sustainability 14.

Sidiq, Fariz, T.R., Saputro, P.A., Sholeh, M., 2024. Built-Up Development Prediction Based on Cellular Automata Modelling Around New Yogyakarta International Airport. Ecol. Eng. Environ. Technol. 25, 238–250. https://doi.org/10.12912/27197050/175138

Sidiq, W., Nur, B., Fariz, T.R., Saputro, P.A., Sholeh, M., 2024. Risk Screening Environmental Indicators Model Change B ased on Spectral Transformation Around New Yogyakarta International Airport. Ecol. Eng. Environ. Technol. 25, 143–160.

Sun, Y., Miao, Y., Zou, Y., Jing, X., 2026. Urban Green Spaces Under Dual Pressures of Human Activity and Climate Change : A Comprehensive Review. Sustainability 18, 1–33. https://doi.org/https://doi.org/10.3390/su18052365

Tesfaye, A.T., 2025. Heliyon Integrated GIS , remote sensing , and analytical hierarchical process approaches to delineate groundwater storage zones in the Sub-Saharan region of Northern Ethiopia. Heliyon 11, e43045. https://doi.org/10.1016/j.heliyon.2025.e43045

Ufaira, R., Amir, S., Indraprahasta, G.S., 2023. Living in a hot city : thermal justice through green open space provision. Front. Hum. Dyn. https://doi.org/doi: 10.3389/fhumd.2023.1237515

Umeike, R., Dao, T., Crawford, S., 2025. Urban Governance State-of-the-art review of resilient smart cities : Progress and challenges. Urban Gov. J. 5, 222–239. https://doi.org/10.1016/j.ugj.2025.05.007

Vujovic, S., Haddad, B., Karaky, H., Sebaibi, N., Boutouil, M., 2021. Urban Heat Island: Causes, Consequences, and Mitigation Measures with Emphasis on Reflective and Permeable Pavements. CivilEng. https://doi.org/10.3390/civileng2020026

Wang, Y., Chen, X., Gao, M., Dong, J., 2022. The use of random forest to identify climate and human interference on vegetation coverage changes in southwest China. Ecol. Indic. 144, 109463. https://doi.org/10.1016/j.ecolind.2022.109463

Waśniewski, A., Hościło, A., Aune-lundberg, L., 2023. Remote Sensing Applications : Society and Environment The impact of selection of reference samples and DEM on the accuracy of land cover classification based on Sentinel-2 data. Remote Sens. Appl. Soc. Environ. 32, 101035. https://doi.org/10.1016/j.rsase.2023.101035

Xi, H., Li, Y., Hou, W., 2025. Impact of Environmental Factors on Summer Thermal Comfort of Ribbon Waterfront Park in Hot Summer and Cold Winter Regions : A Case Study of Hefei. Sustainability.

Xia, L.P. and Q., 2023. Urban Development Boundary Setting Versus Ecological Security and Internal Urban Demand : Evidence from. Land 12. https://doi.org/https://doi.org/10.3390/land12112018

Yin, Y., 2024. Cooling Benefits of Urban Tree Canopy : A Systematic Review. Sustainability 16. https://doi.org/https://doi.org/10.3390/ su16124955

Zhang, J., Ullah, S., Tariq, A., 2026. Linking urban expansion to thermal stress : assessing land use transitions, spectral dynamics, and surface temperature in Burewala. Env. Monit Assess.

Zhang, Z., Zheng, L., Yu, D., 2023. Non-Grain Production of Cultivated Land in Hilly and. Land 12. https://doi.org/https://doi.org/10.3390/land12081562

Zhao, L., Fan, X., Hong, T., 2025. Urban Heat Island Effect : Remote Sensing Monitoring and Assessment — Methods, Applications, and Future Directions. Atmosphere (Basel). 15, 1–55. https://doi.org/https://doi.org/10.3390/atmos16070791