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Original Article

Analysis of Built-Up Land Changes in Tomohon City from 2019 to 2024 Using Sentinel-2 Imagery and Google Earth Engine

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Abstract

Built-up land expansion is a key indicator of urban development, reflecting population growth, economic activities, infrastructure investment, and spatial transformation. Tomohon City, located in North Sulawesi Province, Indonesia, has experienced rapid urban development over recent years, resulting in significant changes in land use and land cover. Monitoring these changes is essential for understanding urban growth dynamics and supporting evidence-based spatial planning and environmental management. This study aims to analyze the spatial dynamics of built-up land in Tomohon City between 2019 and 2024 using Sentinel-2 satellite imagery processed through the Google Earth Engine (GEE) cloud computing platform. The analysis integrates the Normalized Difference Built-up Index (NDBI) to identify and map built-up areas and the Normalized Difference Vegetation Index (NDVI) to evaluate changes in vegetation cover. Multitemporal Sentinel-2 imagery was processed to generate land cover maps and assess the spatial distribution of urban expansion over the five-year study period. The results reveal a noticeable increase in built-up areas, particularly in zones experiencing residential, commercial, and infrastructure development, accompanied by a reduction in vegetation cover in several urban fringe areas. The integration of NDBI and NDVI proved effective in detecting urban expansion and identifying land cover transitions with high spatial consistency. These findings provide valuable baseline information for monitoring urban growth, evaluating environmental impacts associated with land conversion, and supporting sustainable land management, ecological conservation, and future urban spatial planning policies in Tomohon City.

Keywords: NDBI, NDVI, Spatial Planning, Google Earth Engine

INTRODUCTION

Urban development is an inevitable consequence of population growth, economic transformation, and the continuous expansion of physical infrastructure. As cities evolve, increasing demands for housing, transportation networks, commercial facilities, public services, and industrial activities stimulate the conversion of natural landscapes and agricultural land into built-up areas. Consequently, changes in built-up land have become one of the most important indicators for evaluating urbanization because they directly reflect the intensity of human activities and the spatial transformation of urban environments (Carolin & Kurniati, 2025). The expansion of impervious surfaces, including buildings, roads, parking areas, and other urban infrastructure, not only reshapes the physical landscape but also influences ecological processes, hydrological systems, and environmental quality. The rapid conversion of land associated with urbanization has generated numerous environmental challenges worldwide. The replacement of vegetated surfaces with impervious materials reduces infiltration capacity, increases surface runoff, accelerates flood risk, alters local microclimates, and contributes to the formation of Urban Heat Island (UHI) phenomena. Furthermore, extensive land conversion often fragments natural

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ecosystems, reduces biodiversity, and weakens the ecological resilience of urban landscapes. These environmental consequences have intensified global concerns regarding sustainable urban development, emphasizing the importance of balancing economic growth with environmental conservation through evidence-based spatial planning and land management strategies (Sumastono, Surya, & Syafri, 2023). Accurate information regarding the spatial dynamics of built-up land is therefore essential for supporting urban planning, environmental monitoring, and sustainable development policies. Temporal analysis of land cover change provides valuable insights into the direction, magnitude, and rate of urban expansion while enabling local governments to identify areas experiencing rapid development and potential environmental degradation. Such information is increasingly required to evaluate the effectiveness of existing spatial planning regulations, anticipate future land demand, and formulate adaptive strategies for sustainable urban growth.

Tomohon City, located in North Sulawesi Province, Indonesia, represents one of the rapidly developing urban centers in eastern Indonesia. Since becoming an autonomous municipality in 2003, Tomohon has experienced substantial physical and socioeconomic development. Its strategic location adjacent to Manado City has strengthened its role as a regional center for residential development, commerce, tourism, education, and public services. The city's mountainous landscape, relatively cool climate, and tourism potential have further accelerated urban expansion through increasing investment in housing, hospitality facilities, transportation infrastructure, and commercial activities. These developments have inevitably increased demand for land, resulting in the gradual conversion of agricultural areas, plantations, and natural vegetation into built-up land (Djafar, Lihawa, & Maryati, 2025). Previous studies have documented significant land use and land cover changes within Tomohon City, particularly the reduction of plantation areas and vegetated landscapes due to expanding residential settlements and urban infrastructure (Sinaga, Sinurat, & Saragih, 2025). Although these studies have provided valuable information regarding land conversion, continuous monitoring remains necessary because urban growth is highly dynamic and influenced by demographic changes, economic development, government policies, and infrastructure investment. Updated spatial information is particularly important for evaluating whether current urban expansion aligns with sustainable spatial planning objectives while minimizing adverse environmental impacts.

Remote sensing technology has become one of the most reliable approaches for monitoring land cover dynamics because it provides consistent, repetitive, and spatially comprehensive observations of the Earth's surface (Santoso, 2025). Compared with conventional field surveys, satellite-based remote sensing enables efficient monitoring of large geographical areas over multiple time periods while reducing both time and operational costs. The availability of multitemporal satellite imagery has significantly improved the ability of researchers and planners to detect urban expansion, evaluate land cover transitions, and analyze long-term environmental change. Among the various satellite systems currently available, Sentinel-2 imagery has become one of the most widely utilized data sources for urban land cover mapping. The satellite provides multispectral imagery with a spatial resolution of up to 10 meters and frequent revisit intervals, enabling detailed identification of built-up areas and other land cover types (Rotua, n.d.). These characteristics make Sentinel-2 particularly suitable for detecting changes in urban morphology, especially in rapidly developing cities where land conversion occurs continuously over relatively short periods.

The advancement of cloud-based geospatial computing has further enhanced the efficiency of remote sensing analysis. Google Earth Engine (GEE) provides a powerful platform for processing extensive satellite image archives without requiring high-performance local computing resources. By integrating large-scale satellite datasets with cloud computing capabilities, GEE enables rapid image preprocessing, classification, change detection, and spatial analysis across multiple temporal periods. Consequently, the platform has become increasingly popular for environmental monitoring and urban studies because it substantially reduces computational complexity while maintaining analytical accuracy. Numerous recent studies have demonstrated that the integration of Sentinel-2 imagery with Google Earth Engine provides an effective framework for mapping built-up areas and monitoring urban expansion (Irsan & Hasanah, 2025a). Spectral indices such as the Normalized Difference Built-up Index (NDBI) have been widely applied to distinguish impervious urban surfaces from surrounding vegetation and agricultural land. When combined with multitemporal satellite imagery, these techniques enable researchers to evaluate patterns of urban growth, identify spatial directions of expansion, quantify land

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conversion rates, and assess environmental changes associated with urbanization (Irsan & Hasanah, 2025b).

Despite the growing number of studies on urban development in Indonesia, comprehensive analyses focusing specifically on the recent dynamics of built-up land in Tomohon City remain relatively limited. Updated assessments are particularly important considering the city's rapid physical development and its increasing strategic role within the Manado metropolitan region. Understanding the spatial characteristics of built-up land expansion is essential for supporting sustainable urban development while maintaining ecological balance and environmental quality. Therefore, this study aims to analyze changes in built-up land in Tomohon City during the 2019–2024 period using Sentinel-2 satellite imagery processed through the Google Earth Engine platform (Lestari, Mukhlis, & Deril, 2024). By employing remote sensing techniques to examine multitemporal urban expansion, this research seeks to identify the magnitude, spatial distribution, and development patterns of built-up land throughout the study area (Rorong et al., 2024). The findings are expected to contribute to a better understanding of urban growth dynamics and provide scientific evidence that can support sustainable land management, environmental conservation, and the formulation of adaptive spatial planning policies for Tomohon City in the future.

MATERIALS AND METHODS

This study was conducted in Tomohon City, North Sulawesi Province, Indonesia, an area characterized by a heterogeneous landscape comprising residential settlements, agricultural land, plantations, and natural vegetation (Merlin Wilhelmina Singkoh, Rumondor, & Sondakh, 2024). Owing to its strategic location adjacent to Manado City, Tomohon has experienced rapid urban expansion and considerable land use transformation over recent years. The analysis focused on identifying changes in built-up land that occurred between 2019 and 2024 to evaluate the spatial dynamics of urban growth during the five-year observation period. The study utilized Sentinel-2 MultiSpectral Instrument (MSI) Level-2A satellite imagery obtained through the Google Earth Engine (GEE) cloud-computing platform (Latue, Rakuasa, & Sihasale, 2023). Sentinel-2 Level-2A imagery has undergone atmospheric correction, making it suitable for land cover mapping and change detection. Supporting datasets included the administrative boundary of Tomohon City, high-resolution Google Earth imagery for visual interpretation and validation, and reference sample points used for image classification and accuracy assessment. Satellite image processing was performed entirely within the Google Earth Engine environment, while map visualization, spatial editing, and cartographic presentation were completed using Geographic Information System (GIS) software, including QGIS and ArcGIS.

The analysis of built-up land dynamics was based on two widely applied spectral indices, namely the Normalized Difference Built-up Index (NDBI) and the Normalized Difference Vegetation Index (NDVI). The NDBI was employed to identify and extract built-up areas because of its capability to distinguish impervious urban surfaces from surrounding land cover. The index was calculated using Sentinel-2 Band 11 (Shortwave Infrared, SWIR) and Band 8 (Near Infrared, NIR) according to the following equation:

$$NDBI = \frac{SWIR - NIR}{SWIR + NIR}$$

where SWIR represents Sentinel-2 Band 11 and NIR represents Sentinel-2 Band 8. To complement the built-up area analysis, vegetation conditions were evaluated using the Normalized Difference Vegetation Index (NDVI). This index is widely recognized for measuring vegetation density and vigor by comparing the spectral response of healthy vegetation in the near-infrared and red wavelengths. NDVI was calculated using the following equation:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

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where NIR corresponds to Sentinel-2 Band 8 and Red corresponds to Sentinel-2 Band 4. The integration of NDBI and NDVI enabled a comprehensive evaluation of urban expansion while simultaneously identifying the reduction of vegetated areas associated with land conversion.

Following the generation of the NDBI and NDVI maps, built-up areas were extracted for both observation years, and spatial overlay analysis was performed to quantify changes in built-up land between 2019 and 2024. The magnitude of built-up land change was calculated as:

$$\Delta BU = BU_{2024} - BU_{2019}$$

where ΔBU denotes the total built-up land change, $BU_{(2024)}$ represents the built-up land area in 2024, and $BU_{(2019)}$ represents the built-up land area in 2019. To determine the relative rate of urban growth, the percentage of built-up land change was calculated using the following equation:

$$P = \frac{A_{2024} - A_{2019}}{A_{2019}} \times 100\%$$

where P is the percentage of built-up land change, $A_{(2024)}$ is the built-up area in 2024, and $A_{(2019)}$ is the built-up area in 2019. Finally, the extent of newly developed built-up land was quantified to evaluate the magnitude of urban expansion using the following equation:

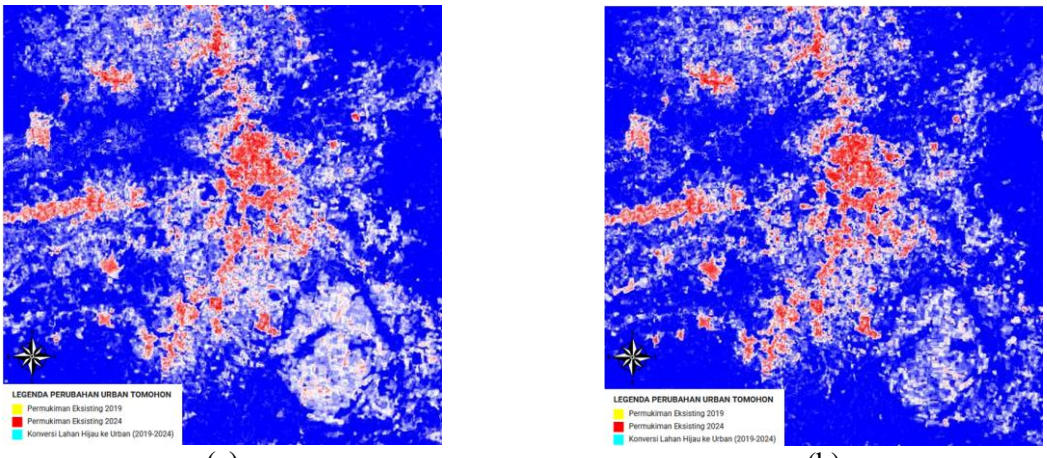
$$E = A_{new} - A_{old}$$

where E represents built-up area expansion, $A_{(new)}$ is the newly developed built-up area, and $A_{(old)}$ is the existing built-up area. The resulting spatial statistics and thematic maps were subsequently interpreted to identify patterns of urban growth, assess the direction of built-up land expansion, and evaluate the implications of land conversion for sustainable urban development and spatial planning in Tomohon City.

RESULTS AND DISCUSSION

A. Spatial Analysis of Built-Up Density (NDBI) in 2019 to 2024

To further examine the spatial dynamics of urban development, the distribution of built-up areas was analyzed using the Normalized Difference Built-up Index (NDBI). This spectral index is widely recognized as an effective indicator for distinguishing impervious urban surfaces from vegetation and other non-built-up land cover based on their spectral reflectance characteristics. Higher NDBI values generally represent areas with greater concentrations of buildings, roads, and other artificial surfaces, whereas lower or negative values indicate vegetation, agricultural land, and water bodies. By comparing the NDBI maps for 2019 and 2024, it is possible to identify changes in the spatial extent and density of built-up land, thereby providing insights into the direction and intensity of urban expansion in Tomohon City.



(a) (b)

Figure 1. NDBI Map of Built-up Density in Tomohon City: (a) 2019 and (b) 2024

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The spatial distribution of built-up land in Tomohon City was analyzed using the Normalized Difference Built-up Index (NDBI), one of the most widely adopted spectral indices for distinguishing impervious urban surfaces from vegetated and non-built-up land. The NDBI exploits the contrasting spectral responses of shortwave infrared (SWIR) and near-infrared (NIR) wavelengths, allowing built-up areas to be identified with relatively high accuracy from Sentinel-2 imagery. Consequently, the index has become an effective tool for monitoring urban growth, quantifying land-use change, and supporting sustainable urban planning through multitemporal remote sensing analysis (Gaur and Singh, 2023) . The 2019 NDBI map demonstrates that built-up areas were predominantly concentrated within the central part of Tomohon City, whereas the surrounding landscape remained largely dominated by agricultural land, plantations, and natural vegetation. Areas exhibiting high positive NDBI values appeared mainly around the historical urban core, reflecting the concentration of residential neighborhoods, commercial facilities, government offices, educational institutions, and transportation infrastructure. In contrast, the peripheral areas were characterized by low or negative NDBI values, indicating that vegetation and other non-built-up land covers continued to dominate the urban fringe. This spatial configuration suggests that urban development in 2019 was still relatively compact, with most development activities occurring within the existing city center rather than expanding extensively into suburban areas. Such a development pattern is commonly observed in medium-sized cities during the initial stages of urbanization, where urban growth remains concentrated around established economic and administrative centers before gradually expanding toward surrounding rural landscapes. Compact urban forms generally reflect lower levels of land conversion and reduced fragmentation of natural ecosystems, thereby maintaining relatively balanced interactions between built-up areas and surrounding green spaces. Similar urban development trajectories have been documented in numerous developing cities where urban expansion initially follows existing transportation corridors and gradually extends outward as population growth and economic activities intensify.

Comparison between the 2019 and 2024 NDBI maps reveals a clear increase in both the spatial extent and density of built-up land throughout Tomohon City. Areas characterized by high positive NDBI values expanded considerably beyond the historical urban core and became increasingly interconnected across multiple directions. This outward expansion reflects the continuous development of residential areas, commercial establishments, public facilities, and supporting infrastructure that accompanied the city's socioeconomic growth during the five-year observation period. The observed expansion also indicates increasing demand for urban land associated with population growth, improved accessibility, and regional economic development. The spatial pattern further indicates that urban growth predominantly occurred adjacent to existing settlements and along major transportation corridors. Such a pattern represents a combination of edge expansion and urban infill, whereby previously fragmented urban patches gradually merged into a more continuous built-up landscape. These findings are consistent with contemporary urban growth theories, which suggest that expanding cities typically develop through the simultaneous processes of peripheral expansion and internal densification. As transportation accessibility improves, vacant parcels located between existing developments are progressively converted into urban land, resulting in increasingly compact yet spatially extensive urban forms.

Despite the noticeable increase in built-up areas, the 2024 NDBI map also indicates that extensive areas with low NDBI values remain distributed throughout much of Tomohon City. These areas correspond primarily to forests, plantations, agricultural land, and other vegetated landscapes that continue to perform essential ecological functions. The persistence of substantial green spaces suggests that Tomohon has not yet experienced complete landscape fragmentation, unlike many rapidly urbanizing metropolitan regions where impervious surfaces dominate most of the urban environment. The coexistence of expanding built-up areas and extensive vegetation presents an important opportunity for implementing sustainable urban development strategies. Vegetated landscapes contribute significantly to ecosystem services through carbon sequestration, biodiversity conservation, groundwater recharge, erosion control, and local climate regulation. Green spaces also mitigate the environmental impacts associated with increasing impervious surfaces by enhancing evapotranspiration, reducing surface runoff, and moderating land surface temperatures. Consequently, maintaining the balance between urban expansion and environmental conservation should become a central objective of future spatial planning in Tomohon City (Gupta et al., 2023).

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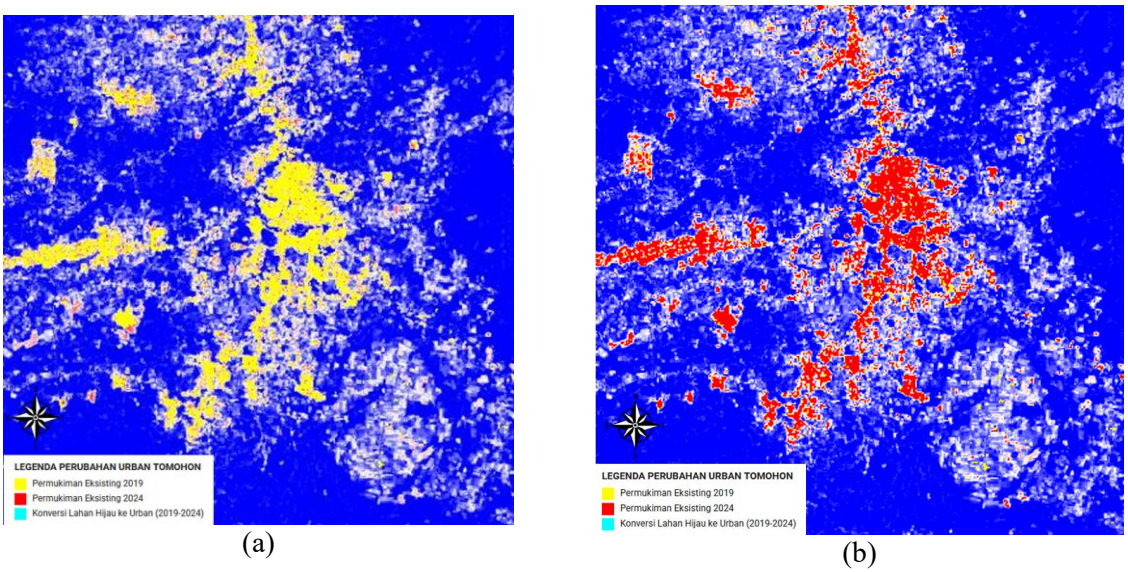
Overall, the multitemporal NDBI analysis demonstrates that Tomohon City experienced significant urban expansion between 2019 and 2024 while still retaining considerable vegetated land. The observed spatial changes indicate an ongoing transition from a relatively compact urban structure toward a more spatially extensive urban landscape. These findings confirm that NDBI derived from Sentinel-2 imagery provides an effective and reliable approach for monitoring urban expansion and evaluating land-use dynamics. Moreover, the resulting spatial information offers valuable scientific evidence for supporting sustainable land-use planning, controlling uncontrolled urban sprawl, preserving green open spaces, and promoting environmentally balanced urban development in Tomohon City.

B. Existing Residental Areas in 2019 to 2024

To better understand the spatial dynamics of urban growth in Tomohon City, the built-up land identified from the NDBI analysis was further classified into existing residential areas for both 2019 and 2024. This classification provides a clearer visualization of the distribution, concentration, and expansion of settlements over time, allowing changes in urban morphology to be more readily interpreted. Comparing the settlement patterns between the two periods enables the identification of urban expansion trends, the direction of residential growth, and the transformation of previously undeveloped land into built-up areas. These spatial patterns also provide valuable insights into the ongoing urbanization process and its implications for future land use planning and sustainable urban development.



(a) (b)

Figure 2. Existing Residental Areas: (a) 2019 and (b) 2024

The 2019 existing settlement map shows built-up residential areas represented in yellow. These settlements are primarily concentrated in the city center and follow the main transportation corridors. At that time, the built-up area remained relatively limited and was scattered across several locations. This spatial pattern indicates that the urbanization process in Tomohon City was still in its early stage of development. The 2024 settlement map uses red to represent built-up residential areas. Compared with 2019, both the extent and density of settlements have increased. Urban development has expanded beyond the city center into surrounding suburban areas. This trend indicates an increasing demand for land to accommodate residential development, commercial activities, and other urban functions.

C. Newly Developed Urban Areas

To further identify the spatial pattern of urban expansion, a change detection analysis was conducted to distinguish newly developed built-up areas from existing settlements. By comparing the built-up land classifications for 2019 and 2024, areas that experienced land conversion during the five-year period were extracted and mapped. This approach provides a clear representation of the direction and magnitude of urban expansion while highlighting the locations where development has been most

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intensive. The resulting map serves as an important basis for understanding the dynamics of urban growth and evaluating its implications for land use management, infrastructure development, and sustainable urban planning in Tomohon City.

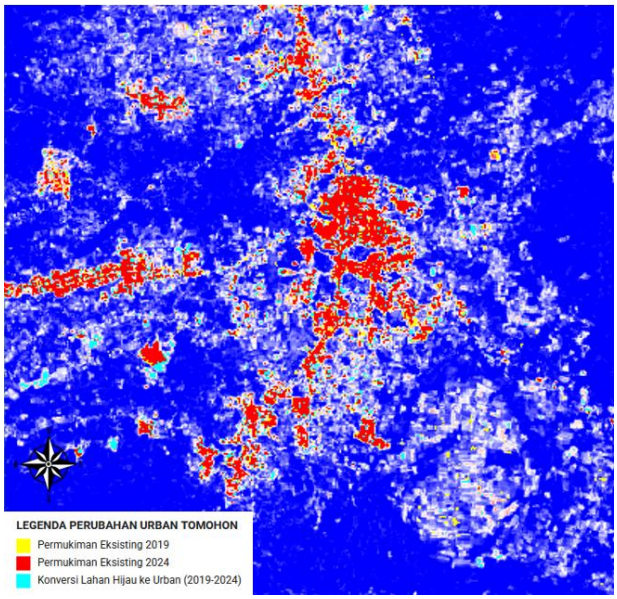

Figure 3. Newly Developed Urban Areas (Cyan)

The map of newly developed urban areas provides a clear visualization of land that was transformed into built-up surfaces between 2019 and 2024, with newly developed areas represented in cyan. The spatial distribution indicates that urban expansion occurred predominantly adjacent to existing residential areas and followed the alignment of the primary transportation network. This spatial configuration demonstrates that urban growth in Tomohon City has mainly occurred through edge expansion, where new development extends outward from the existing urban fabric rather than emerging as isolated patches. Such a growth pattern is characteristic of medium-sized cities undergoing gradual urbanization, in which accessibility, transportation infrastructure, and proximity to public facilities become the principal drivers of land conversion. Transportation corridors increase land accessibility, stimulate investment, and subsequently accelerate residential and commercial development along major roads (Taubenböck et al., 2012; Seto et al., 2012).

The spatial pattern observed in Tomohon City is consistent with the theory of urban expansion, which suggests that cities generally develop through contiguous outward growth before experiencing leapfrog development in more distant peri-urban areas. The availability of road infrastructure reduces transportation costs and improves accessibility to economic opportunities, making surrounding land increasingly attractive for urban development. Consequently, agricultural land and vegetated areas located near existing settlements become the most vulnerable to conversion into residential neighborhoods, commercial facilities, and supporting infrastructure. Similar development trajectories have been documented in numerous rapidly growing cities across Southeast Asia, where transportation infrastructure functions as the primary catalyst for urban expansion and land-use transformation (Seto et al., 2012).

Table 1. Quantification of Land Change and Urban Expansion in Tomohon City

Spatial Metric	Area (ha)	Percentage Change (%)
Delineated Residential Area (2019)	331.57	–
Delineated Residential Area (2024)	342.02	–
Converted Urban Green Space	86.03	+25.15

Source: *Authors Analysis, 2026*

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The quantitative analysis presented in Table 1 confirms these spatial observations. Residential areas increased from 331.57 ha in 2019 to 342.02 ha in 2024, representing an expansion of 10.45 ha, or approximately 3.15% during the five-year observation period. Although this increase appears relatively modest in percentage terms, the spatial distribution demonstrates that development occurred strategically around existing built-up areas rather than through dispersed urban sprawl. This compact expansion pattern indicates relatively efficient land utilization because new development largely benefited from existing transportation networks and public infrastructure. Compact urban development is generally associated with lower infrastructure costs, improved accessibility, and reduced fragmentation of surrounding landscapes compared with uncontrolled urban sprawl (Angel et al., 2011). More importantly, the analysis indicates that approximately 86.03 ha of urban green space were converted into built-up land during the study period, representing a 25.15% decline in vegetated urban land. This finding reflects increasing development pressure on ecological landscapes within Tomohon City. Urban green spaces provide a wide range of ecosystem services, including regulation of local microclimate, enhancement of groundwater infiltration, reduction of surface runoff, mitigation of flood hazards, conservation of biodiversity, carbon sequestration, and improvement of urban environmental quality. Consequently, the continued conversion of vegetated land into impervious surfaces may significantly reduce the capacity of urban ecosystems to regulate environmental processes and maintain ecological stability (Demuzere et al., 2014). The reduction in vegetated areas is also expected to modify the city's physical and thermal environment. Built-up materials such as concrete, asphalt pavement, and roofing materials generally exhibit higher heat capacity and lower evapotranspiration than vegetated surfaces. As impervious surface coverage increases, greater quantities of solar radiation are absorbed during the daytime and gradually released as sensible heat, contributing to elevated land surface temperatures and the formation of urban heat islands. Simultaneously, declining vegetation reduces evaporative cooling and decreases rainfall infiltration, thereby increasing surface runoff and reducing groundwater recharge. Numerous studies have demonstrated that rapid urban expansion accompanied by vegetation loss substantially alters urban energy balance, hydrological processes, and local climatic conditions (Oke, 1982; Weng, 2001).

The satellite image analysis further supports these observations. Processing Sentinel-2 imagery using the Normalized Difference Built-up Index (NDBI) shows a clear increase in areas characterized by high positive NDBI values between 2019 and 2024. High NDBI values correspond to impervious surfaces such as residential buildings, commercial facilities, roads, and other urban infrastructure because these materials exhibit stronger reflectance in the shortwave infrared (SWIR) region than in the near-infrared (NIR) region. The NDBI algorithm, originally introduced by Zha et al. (2003), has become one of the most widely adopted spectral indices for mapping built-up land because of its ability to distinguish urban surfaces from vegetation and water bodies with relatively high accuracy. Complementary analysis using the Normalized Difference Vegetation Index (NDVI) indicates a noticeable reduction in vegetation cover within areas experiencing residential expansion. The inverse spatial relationship between NDBI and NDVI observed in this study confirms that the expansion of impervious surfaces has occurred largely at the expense of vegetated land. Similar relationships have been consistently reported in remote sensing studies, where increasing built-up density is generally associated with declining vegetation cover and deteriorating ecological conditions (Weng, 2001). Despite these changes, the relatively moderate rate of residential expansion suggests that Tomohon City still possesses substantial opportunities to implement sustainable urban development strategies. Future urban growth should prioritize compact development within existing urban areas while preserving ecologically valuable landscapes, including urban forests, agricultural land, riparian vegetation, and other green open spaces. Integrating green infrastructure into urban planning is essential for maintaining ecosystem services, regulating urban microclimates, improving stormwater management, and enhancing long-term climate resilience (Demuzere et al., 2014).

Overall, the integration of multitemporal Sentinel-2 imagery with Google Earth Engine demonstrates that Tomohon City experienced gradual but continuous urban expansion during the 2019–2024 period. Although residential development remained relatively compact, the conversion of approximately 86 ha of urban green space indicates increasing ecological pressure associated with land-use change. These findings highlight the importance of strengthening spatial planning policies that balance urban development with environmental conservation. Sustainable urban growth should

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therefore emphasize the protection of green infrastructure, the efficient utilization of existing built-up land, and the preservation of ecosystem functions to ensure long-term environmental quality and urban resilience.

CONCLUSION

This study demonstrates that Tomohon City experienced continuous urban expansion between 2019 and 2024, resulting in measurable changes in land-use patterns. The increase in built-up areas, as identified through the Normalized Difference Built-up Index (NDBI), indicates the ongoing conversion of vegetated land into urban land uses. Conversely, the Normalized Difference Vegetation Index (NDVI) analysis reveals a decline in vegetation cover, particularly in areas undergoing residential and infrastructure development. The spatial pattern of urban expansion, which generally follows major transportation corridors and economic centers, highlights the important role of accessibility in shaping the city's growth. These findings are consistent with established theories of urban development and land-cover change. The results also demonstrate the effectiveness of integrating Sentinel-2 satellite imagery with the Google Earth Engine platform for monitoring urban expansion and land-use change. The generated spatial information provides valuable support for urban planning, land-use management, and the protection of urban green spaces. Maintaining a balance between urban development and environmental conservation is essential to promote sustainable urban growth and preserve ecosystem functions in Tomohon City. Future research should extend the observation period to provide a more comprehensive understanding of long-term urban expansion patterns and rates. The incorporation of additional built-up indices, such as the Index-Based Built-up Index (IBI) and the Enhanced Built-up and Bareness Index (EBBI), may further improve the accuracy of built-up land identification. Moreover, future studies are encouraged to examine the relationships between urban expansion and other influencing factors, including population growth, road accessibility, land surface temperature, and changes in urban green spaces, to better understand the broader environmental and socio-spatial impacts of urban development in Tomohon City.

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