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Monitoring Ekspansi Perkotaan dan Defisit Ruang Terbuka Hijau di Jakarta dan Bandung Tahun 2017–2025 Menggunakan Citra Sentinel-2, Algoritma Random Forest, dan GEE

Monitoring Urban Expansion and Green-Space Deficits in Jakarta and Bandung (2017–2025) Using Sentinel-2, Random Forest, and GEE

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Abstract: *Rapid urban growth in Indonesia is increasing pressure on the legal requirement that cities maintain at least 30% Green Open Space (Ruang Terbuka Hijau). This study examines land use/land cover change and vegetation dynamics in Jakarta and Bandung from 2017 to 2025 using Sentinel-2 Level-2A imagery, multiple spectral indices, and Random Forest classification implemented in Google Earth Engine. Four classes were mapped annually: Vegetation, Urban, Water, and Open Land. The classification performed well, with mean overall accuracy above 94% and Kappa around 0.9. Despite similar technical performance, the two cities show contrasting ecological trajectories. Jakarta remains structurally under-greened, with vegetation increasing only from 8.1% in 2017 to 9.3% in 2025, far below the 30% benchmark. Bandung instead undergoes rapid green space loss, with vegetation declining from 22.17 km² to 8.53 km², a net loss of over 61% in less than a decade. These findings indicate that a single national target can mask divergent local realities: Jakarta faces a restoration challenge in a saturated built environment, whereas Bandung must prioritize protection of remaining vegetated land at its urban outskirts. The workflow presented in this study provides a GeoAI-based monitoring approach that can be replicated for other Indonesian cities.*

Kata kunci: Perubahan penggunaan lahan, Penurunan tutupan vegetasi, Random Forest, Sentinel-2, Google Earth Engine, Jakarta, Bandung, ruang terbuka hijau (RTH).

Abstrak: Pertumbuhan perkotaan yang pesat di Indonesia semakin meningkatkan tekanan terhadap pemenuhan ketentuan hukum yang mewajibkan kota memiliki sedikitnya 30% Ruang Terbuka Hijau (RTH). Penelitian ini menganalisis perubahan penggunaan/tutupan lahan serta dinamika vegetasi di Jakarta dan Bandung selama periode 2017–2025 menggunakan citra Sentinel-2 Level 2A, berbagai indeks spektral, dan klasifikasi Random Forest yang diimplementasikan pada platform Google Earth Engine. Empat kelas tutupan lahan dipetakan setiap tahun, yaitu vegetasi, kawasan terbangun, badan air, dan lahan terbuka. Hasil klasifikasi menunjukkan kinerja yang sangat baik dengan nilai akurasi keseluruhan rata-rata di atas 94% dan koefisien Kappa sekitar 0,9. Meskipun memiliki performa klasifikasi yang serupa, kedua kota menunjukkan kondisi ekologis yang berbeda. Jakarta masih mengalami kekurangan ruang hijau secara struktural, dengan proporsi vegetasi yang hanya meningkat dari 8,1% pada tahun 2017 menjadi 9,3% pada tahun 2025, jauh di bawah target 30%. Sebaliknya, Bandung mengalami penurunan ruang hijau yang signifikan, dengan luas vegetasi berkurang dari 22,17 km² menjadi 8,53 km² atau kehilangan bersih lebih dari 61% dalam kurun waktu kurang dari satu dekade. Temuan ini menunjukkan bahwa penerapan target nasional yang seragam dapat menutupi perbedaan kondisi lokal yang mendasar. Jakarta menghadapi tantangan restorasi ruang hijau di lingkungan yang telah didominasi kawasan terbangun, sedangkan Bandung perlu memprioritaskan perlindungan lahan bervegetasi yang tersisa di wilayah pinggiran kota. Alur kerja berbasis GeoAI yang dikembangkan dalam penelitian ini menawarkan pendekatan pemantauan yang dapat direplikasi untuk kota-kota lain di Indonesia.

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1. INTRODUCTION

Large Indonesian cities have been changing quickly as population growth, economic expansion, and infrastructure development compete for limited urban land. In places such as Jakarta and Bandung, agricultural areas, vacant land, and green spaces on the city outskirts have increasingly been converted into residential, commercial, and industrial uses. This transition often moves faster than the ability of planning institutions to control it effectively. Under Law No. 26 of 2007 on Spatial Planning, each urban area is mandated to have at least 30% of its area as Green Open Space (UU 26 Tahun 2007, 2007), consisting of 20% public and 10% private green space. In practice, however, many cities remain well below that threshold.

Bandung is a clear example of this long-running gap between policy and actual land conditions. Previous reporting has shown that formal green space in the city remains far below the required 30%, reflecting persistent tension between urban growth and ecological protection (Sarah Ashilah, 2022). Conventional field-based monitoring methods such as total station surveys and geodetic GPS can produce accurate local observations, but they are too slow and expensive to support regular city-scale monitoring (Hassan et al., 2019). The spread of freely available satellite data and cloud-based geospatial platforms has changed this situation. Sentinel-2 imagery, combined with Google Earth Engine, now allows urban land change to be observed repeatedly and consistently over wide areas.

This study focuses on Jakarta and Bandung because they represent different stages of urbanization within Indonesia. Jakarta is already dominated by built-up land and has very little residual open space left, while Bandung still contains sizable vegetated areas but is undergoing active outward expansion. Despite growing work on urban remote sensing in Southeast Asia, systematic studies that couple multi-year machine-learning LULC time series with explicit assessment of statutory 30% RTH compliance across contrasting Indonesian cities remain very limited, leaving a critical gap between remote sensing outputs and regulatory monitoring practice. For that reason, this research uses Sentinel-2 imagery and Random Forest classification in a reproducible GeoAI workflow to examine how land-use patterns and vegetation cover changed from 2017 to 2025, and what those trajectories mean for compliance with the national RTH mandate.

2. MATERIALS AND METHODS

2.1 Study Area

The main study area is DKI Jakarta, which covers approximately 662.33 km² of mainland territory, excluding the Thousand Islands (Kepulauan Seribu). Administratively, Jakarta consists of five municipalities: Central, North, East, South, and West Jakarta. The city is characterized by dense built-up land, limited remaining vegetation, and a range of environmental pressures such as flooding and air pollution. Bandung City was selected as a second study area and comparative case. With an area of about 168.1 km², Bandung provides a useful contrast because it represents a rapidly expanding secondary city where growth on the city outskirts remains active.

Both study areas were analyzed at 10 m spatial resolution using Sentinel-2 imagery in the WGS 84 / UTM Zone 48S coordinate system. The temporal coverage spans 2017 to 2025. The year 2017 was used as the baseline for cumulative change analysis, while the full annual sequence was used to reconstruct the trajectories of land-use and vegetation dynamics in each city.

2.2 Data and Pre-processing

The analysis used Sentinel-2 Level-2A surface reflectance imagery accessed through Google Earth Engine (GEE), a cloud-based platform that is widely used for large-scale urban monitoring and can support the production of highly accurate change products (Xu et al., 2024). For each year from 2017 to 2025, images were filtered to cloud-cover conditions below 15% and combined into annual median composites. A full-year compositing window from January to December was selected to maximize the number of usable observations and reduce the influence of clouds, atmospheric noise, and short-term disturbances. The resulting imagery was clipped to the administrative boundaries of Jakarta and Bandung.

The predictor dataset included Blue (B2), Green (B3), Red (B4), Red Edge (B5-B7), NIR (B8), and SWIR (B11-B12) bands. Digital numbers were divided by 10,000 to obtain normalized surface reflectance. Because Sentinel-2 Level-2A products are already corrected geometrically and atmospherically, pre-processing mainly concentrated on band selection, annual compositing, and derivation of spectral indices. Administrative boundaries and high-resolution imagery from sources such as Google Earth and Bing Maps were also used to guide the interpretation of training samples and validation points.

2.3 Feature Extraction

In order to improve class separability, the study combined spectral bands with several widely used indices. These included NDVI, NDWI, NDBI, NDMI, SAVI, and EVI. Together, these features capture vegetation vigor, built-up reflectance, soil exposure, and moisture conditions, all of which are important for distinguishing urban land-cover classes.

NDVI was used to emphasize vegetation through the contrast between high NIR and low red reflectance. NDWI was used to highlight open water based on the relationship between green and NIR reflectance. NDBI helped identify built-up land through the contrast between SWIR and NIR. Additional indices such as NDMI, SAVI, and EVI were included to better separate moisture-sensitive surfaces, sparse vegetation, bare soil, and heterogeneous urban environments where mixed pixels and spectral overlap are common.

2.4 Random Forest Classification

LULC classification was carried out in Google Earth Engine using the Random Forest algorithm through ee.Classifier.smileRandomForest. Four classes were mapped: Vegetation, Water, Urban, and Open Land. Random Forest was selected because it is a non-parametric ensemble classifier that performs well with high-dimensional and correlated predictor sets. It builds multiple decision trees using randomly selected subsets of training samples and input variables, assigning the final class based on a majority vote across all trees. It makes no strict assumptions about data distributions and is highly robust to high-dimensional, collinear data (Belgiu & Drăguţ, 2016), while also being relatively insensitive to noise in training samples and well-suited for multi-band satellite imagery classification (Thanh Noi & Kappas, 2017).

Reference samples were collected using stratified random sampling across both cities. In each year and city, around 100 points were digitized for each class, producing approximately balanced class representation and yielding around 3,600 samples per city overall. Sample points were distributed across central and city outskirts to capture spatial variability and reduce bias. Labels were assigned through visual interpretation of high-resolution imagery and supporting land-use information.

The model used 70% of the samples for training and 30% for independent validation, and each annual composite for 2017–2025 was classified with an ensemble of 100 decision trees, using default GEE settings for variables per split and tree depth. Performance was assessed using confusion matrices, Overall Accuracy (OA), and Cohen's Kappa coefficient. This setup was intended to maintain comparability across years while supporting reliable multi-year change analysis.

2.5 Change Detection and RTH Assessment

Post-classification change detection was applied to quantify land dynamics from 2017 to 2025. Rather than constructing a full transition matrix for all class combinations, the analysis focused on annual area totals for the four mapped classes. A pixel-based comparison between 2017 and 2025 was then used to identify areas of Vegetation Loss and Vegetation Gain. To suppress noise, only contiguous changes of at least nine pixels were retained using four-directional pixel connectivity.

For the Green Open Space assessment, the combined area of Vegetation and Water was used as a spectral proxy for total RTH. This proxy does not fully replicate the legal distinction between public and private RTH, but it offers a transparent and repeatable indicator of urban greenness that can be tracked consistently through time. Annual proportions were compared against the statutory 30% threshold (UU 26 Tahun 2007, 2007) in order to estimate the scale of green-space deficits in each city, a methodology that has been shown to be effective for geospatial green-space assessment in other Indonesian municipalities (Sufrianto et al., 2025).

3. RESULTS

3.1 Classification Accuracy

The Random Forest classifier achieved consistently high accuracy across all study years and both cities. Classification performance was evaluated using a stratified 70/30 random split of ground truth samples, with Overall Accuracy (OA) and Cohen's Kappa coefficient (κ) computed from confusion matrices constructed using the 30% validation subset. Confusion matrices for each year were generated using the errorMatrix() function in Google Earth Engine with a fixed four-class order (Vegetation, Water, Urban, Open Land) to ensure dimensional consistency across all annual outputs.

3.1.1 Overall Accuracy (OA) and Kappa Trends (κ)

For Jakarta, OA ranged from 90.71% (2020) to 97.87% (2021), with a mean OA of 95.47% and a mean Kappa of 0.9389 across the study period (Figure 1). Bandung showed a comparable level of performance, with OA ranging from 89.32% (2017) to 100.00% (2024) and a mean OA of 94.47%, while the mean Kappa reached 0.9244 (Figure 2). Using the Landis & Koch (1977) interpretation scale, all annual Kappa values fell into the "Almost Perfect Agreement" category (κ ≥ 0.80), indicating that the model consistently distinguished the four land cover classes with high reliability.

The year-to-year stability of Kappa values, with minimal fluctuation around the 0.93–0.92 range for Jakarta and Bandung respectively, further indicates that classification performance was not significantly affected by inter-annual variations in image compositing conditions, atmospheric effects, or training sample distribution. This consistency is particularly important for change detection analyses, as it suggests that observed land-cover trends reflect genuine on-the-ground dynamics rather than methodological artifacts or classification drift.

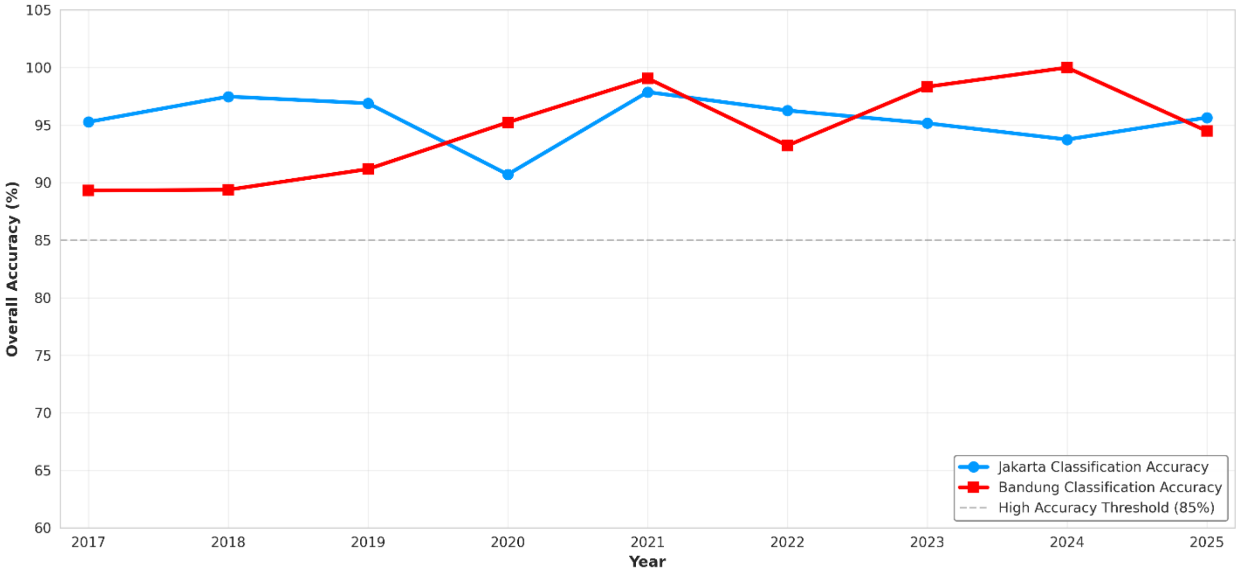

Figure 1. Bandung vs Jakarta Overall Accuracy

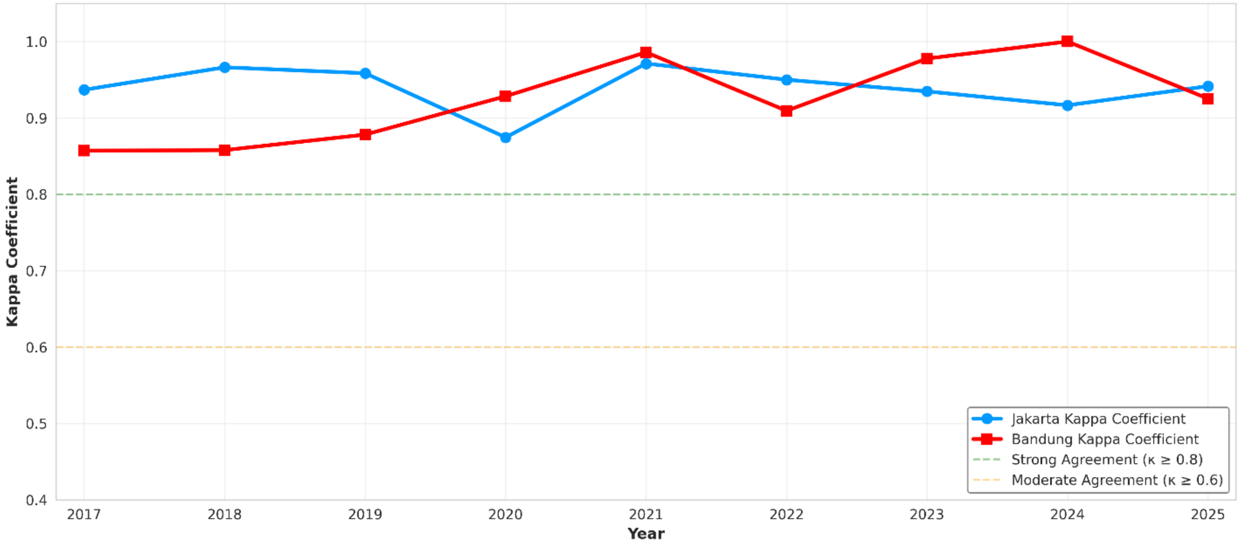

Figure 2. Bandung vs Jakarta Kappa Coefficient trends

3.1.2 Confusion Matrix Analysis and Per-Class Accuracy

Full confusion matrices were extracted for all 18 city–year combinations and aggregated by summing validation counts across all years, then normalizing by reference class. Table 1 and 2 show the results for Jakarta and Bandung respectively, where diagonal values indicate producer's accuracy and off-diagonal cells indicate where samples were misassigned.

Table 1. Aggregated Confusion Matrix — Jakarta (2017–2025)

	Vegetation	**Water**	**Urban**	**Open Land**
Vegetation	**98.22%**	0.00%	0.00%	**1.78%**
Water	0.00%	**97.55%**	**0.61%**	**1.83%**
Urban	0.00%	**0.33%**	**94.37%**	**5.30%**
Open Land	**3.24%**	**0.81%**	**5.26%**	**90.69%**

Table 2. Aggregated Confusion Matrix — Bandung (2017–2025)

	Vegetation	**Water**	**Urban**	**Open Land**
Vegetation	**96.73%**	0.00%	0.00%	3.27%
Water	0.00%	**95.93%**	1.11%	2.96%
Urban	0.00%	1.18%	**96.46%**	2.36%
Open Land	8.82%	0.00%	5.88%	**85.29%**

Three of the four classes, which are Vegetation, Water, and Urban, were classified reliably across both cities. Jakarta's diagonal values reached 98.22%, 97.55%, and 94.37% for those classes, while Bandung returned 96.73%, 95.93%, and 96.46%, respectively. Water was the most consistently identified class in both settings, which was expected given how distinctively open water separates from other surfaces in the NDWI and SWIR bands of Sentinel-2.

Open Land stood out as the most problematic class. In Bandung, 8.82% of Open Land samples were misclassified as Vegetation and another 5.88% as Urban. Jakarta showed a broadly similar pattern, with 5.26% of Open Land confused with Urban and 3.24% with Vegetation. This kind of confusion is not surprising when working at 10 m resolution. Around city outskirts especially, bare or sparsely vegetated ground can share overlapping NDVI and SWIR values with both degraded vegetation patches and low-density built-up areas, a spectral ambiguity that tends to persist regardless of which classifier is applied.

3.2 Land Use and Vegetation Dynamics in Jakarta and Bandung

Neither city follows a clean linear trend across the study period. Annual land-use data for both Jakarta and Bandung show notable fluctuations, particularly between 2020 and 2023 (see Figure 3). Some of this variability likely reflects the temporary drop in construction and mobility activity during the COVID-19 period, a condition that has been linked elsewhere to short-term vegetation recovery in heavily modified urban landscapes (He et al., 2026), followed by renewed development pressure once restrictions lifted and spatial planning governance was restructured (Kementerian ATR/BPN, 2022). Beyond these shared fluctuations, the two cities differ substantially in how land-cover classes are distributed across the study period (see Figure 3).

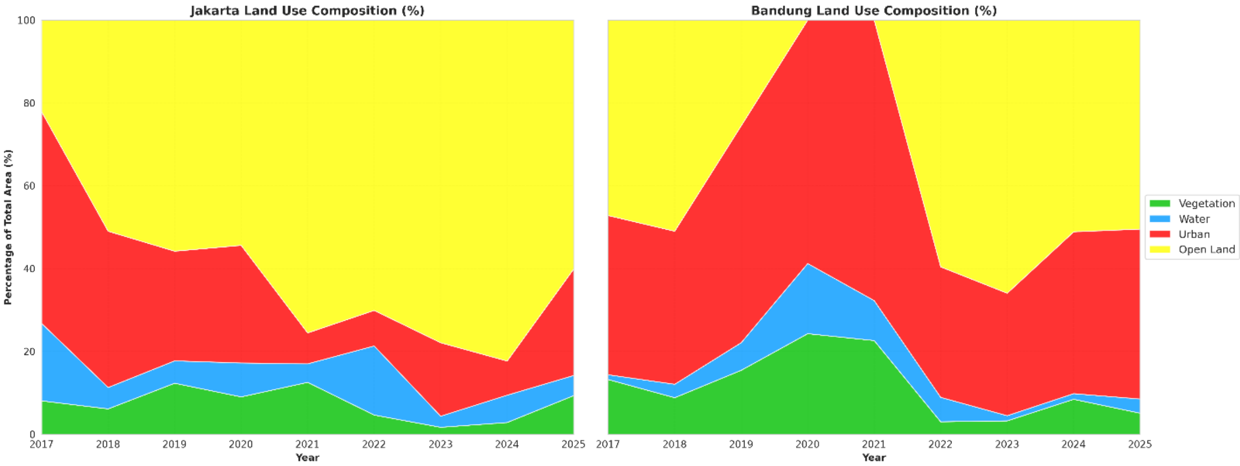

Figure 3. Annual Percentage of Urban and Vegetated Land Cover in Jakarta and Bandung from 2017 to 2025.

The Jakarta time series shows considerable year-to-year movement in both the urban and vegetation curves. Around 2021, there is a noticeable anomaly: mapped urban area dips sharply while the vegetation curve peaks, before vegetation declines again toward 2023 and partially recovers afterward (see Figure 4). This kind of deviation is typical when annual composites vary in cloud conditions or scene quality, and it may also partly capture the genuine short-term relaxation of land conversion during the pandemic. Despite these fluctuations, the quantitative data reveals that Jakarta's landscape has very little empty land left to develop. Vegetation coverage shifted from 52.57 km² (8.1% of total land area) in 2017 to 60.77 km² (9.3%) in 2025, representing a modest net gain of 8.20 km² over eight years. This pattern suggests that Jakarta is running out of convertible land, and green cover remained in the single digits in most years and never approached the 30% benchmark, supporting the interpretation that increasing urban greenness in Jakarta requires targeted, structural interventions rather than relying on passive spatial trends.

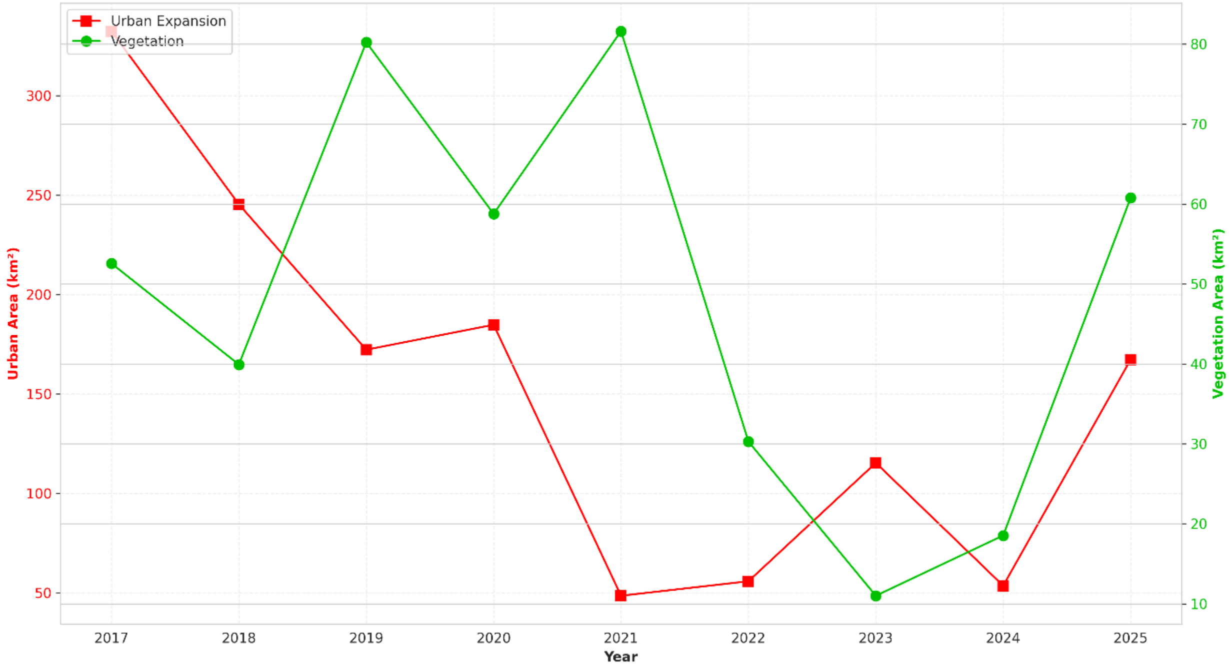

Figure 4. Jakarta Urban Expansion vs Vegetation (2017-2025)

The picture from Bandung is quite different. The urban and vegetation curves move in opposite directions, especially in the second half of the observation window where urban cover rises while vegetation shrinks (Figure 5). The quantitative data confirm this critical loss in which vegetation coverage declined sharply from 22.17 km² (13.2% of the city area) in 2017 to just 8.53 km² (5.1%) in 2025, indicating a net loss of 13.64 km², or about 61.5% of the initial vegetated area, in less than a decade. Both curves show a local peak around 2020–2021, followed by a strong contraction in 2022–2023 and a partial recovery afterward, indicating that development comes in sudden pushes, often coinciding with phases of intensive infrastructure development or land conversion on the city's outskirts.

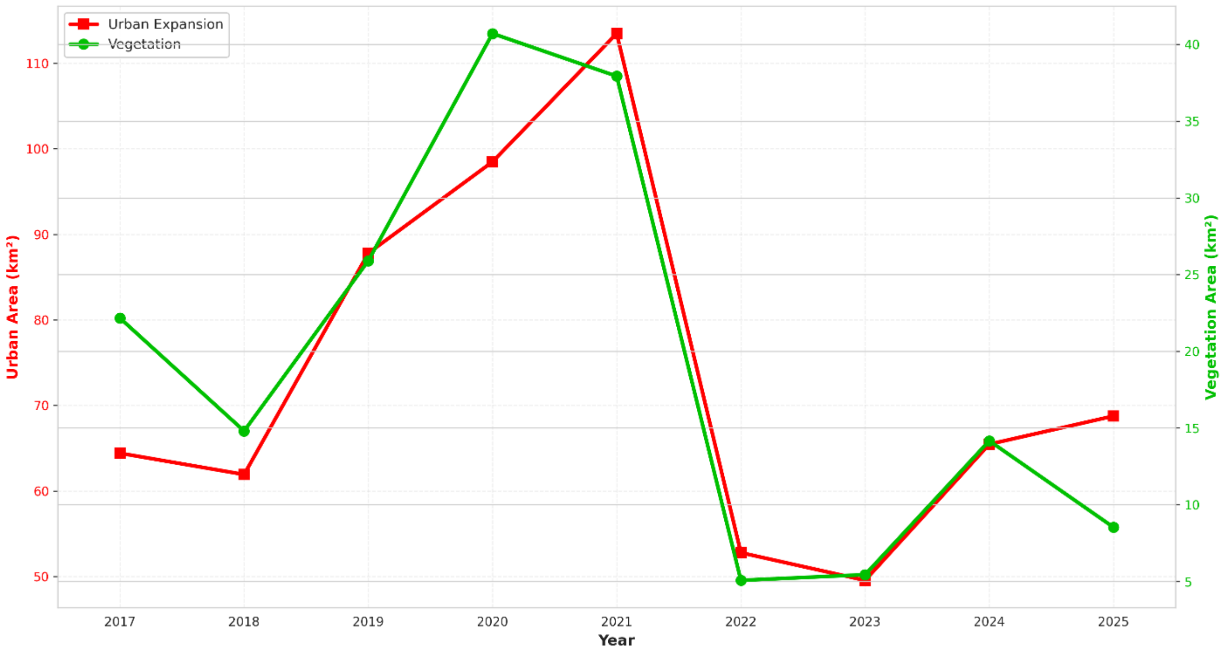

Figure 5. Urban Expansion vs Vegetation (2017-2025) of Bandung city

When the two cities are placed side by side (Figure 3), Bandung's land-use composition shifts far more dramatically over the middle years, while Jakarta's profile stays heavily dominated by the built-up urban class (Figure 3). The crossing trajectories in Bandung mark a critical phase in the city's urbanization process, where continued conversion of green land makes it progressively more difficult to restore RTH to the legally required 30%. Taken together, the data and figures support the central conclusion that policy responses should be city-specific: For Jakarta, the policy problem is about finding space and scale for green cover within an already dense city. For Bandung, it is about stopping ongoing losses before the city reaches Jakarta's level of ecological saturation.

3.3 Comparative Assessment of RTH Compliance

Measured against the statutory 30% RTH threshold, Jakarta and Bandung tell very different stories across the 2017–2025 period (Figure 6). Jakarta's RTH fraction started at 26.77% in 2017, which was close to the legal minimum but still short of it. From there, the figure declining sharply to 11.31% in 2018 and fluctuating roughly between 17% and 21% through 2022. The lowest point came in 2023, when the RTH fraction fell to just 4.37%, before partially recovering to 14.20% by 2025. Even in its better years, Jakarta was consistently running a deficit of more than 15 percentage points against the statutory requirement, indicating that the city was never truly near compliance during this period; it was structurally under-greened state throughout the study period.

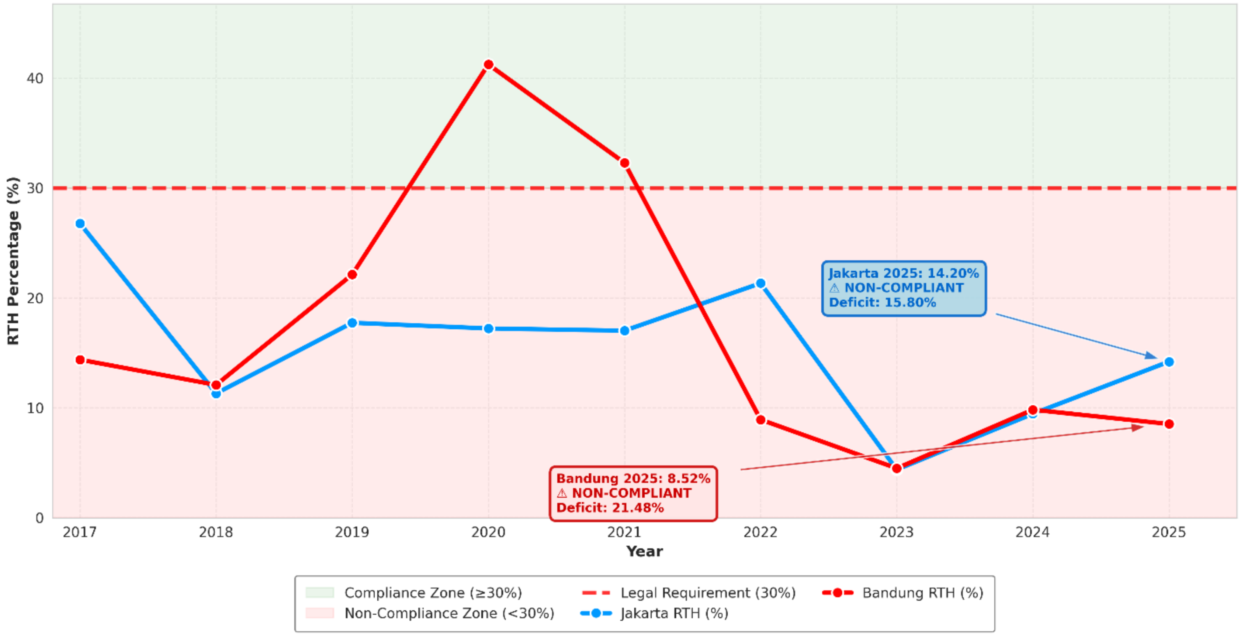

Figure 6. RTH Compliance Comparison of Jakarta vs Bandung 2017-2025

Bandung's trajectory is harder to characterize simply. Unlike Jakarta, Bandung actually crossed the 30% threshold during this period, reaching 41.24% in 2020 and 32.29% in 2021 (as indicated by the red line in Figure 6). For those two years, the city was legally compliant. What followed, however, was a rapid and drastic erosion of its vegetated area in the subsequent years. By 2025, the RTH fraction had collapsed to just 8.52%, leaving the city with a deficit of 21.48 percentage points below the statutory minimum. The speed of that decline is what stands out. This sudden collapse represents a rate of decline far more severe than any fluctuation experienced by Jakarta, and demonstrates a critical failure to preserve existing green assets amid recent urban expansion.

The spatial patterns of cumulative LULC change further emphasize these distinctions. In Jakarta, vegetation gains and losses are scattered across the city in small, disconnected patches (Figure 7). What little green cover exists is confined to narrow riverbanks, isolated parks, and residual pockets surrounded on all sides by dense built-up fabric. There is no coherent spatial logic to the green distribution, which makes it practically very difficult to build connected green corridors or expand green cover in any meaningful way without deliberate land reconfiguration.

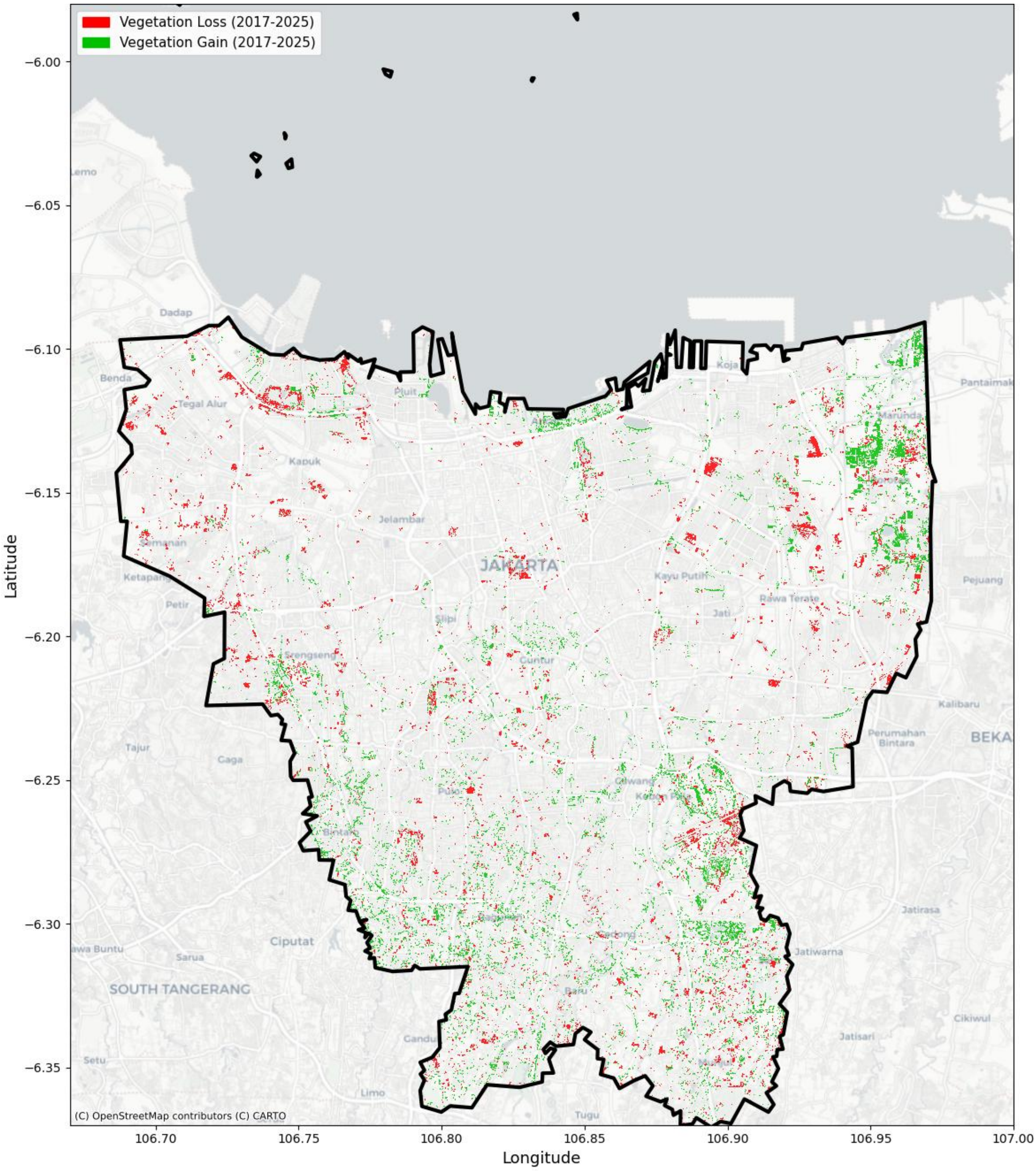

Figure 7. Cumulative Vegetation Change in Jakarta (2017-2025)

Bandung's spatial pattern tells a different story. Within the urban core, changes are relatively scattered, but along the city's outer edges, particularly in the northern, eastern, and southern sectors, large and concentrated clusters of vegetation loss are visible (indicated in red in Figure 8). Gross vegetation loss across the study period totaled 9.40 km², while gains reached only 4.78 km², yielding a net loss of 4.62 km². This spatial structure is characteristic of outward expansion consuming previously intact green land on the city outskrits. Unlike the fragmented losses seen in Jakarta, Bandung is losing contiguous vegetated zones, which breaks apart ecological connectivity and makes future restoration significantly more difficult than if the losses were small and dispersed.

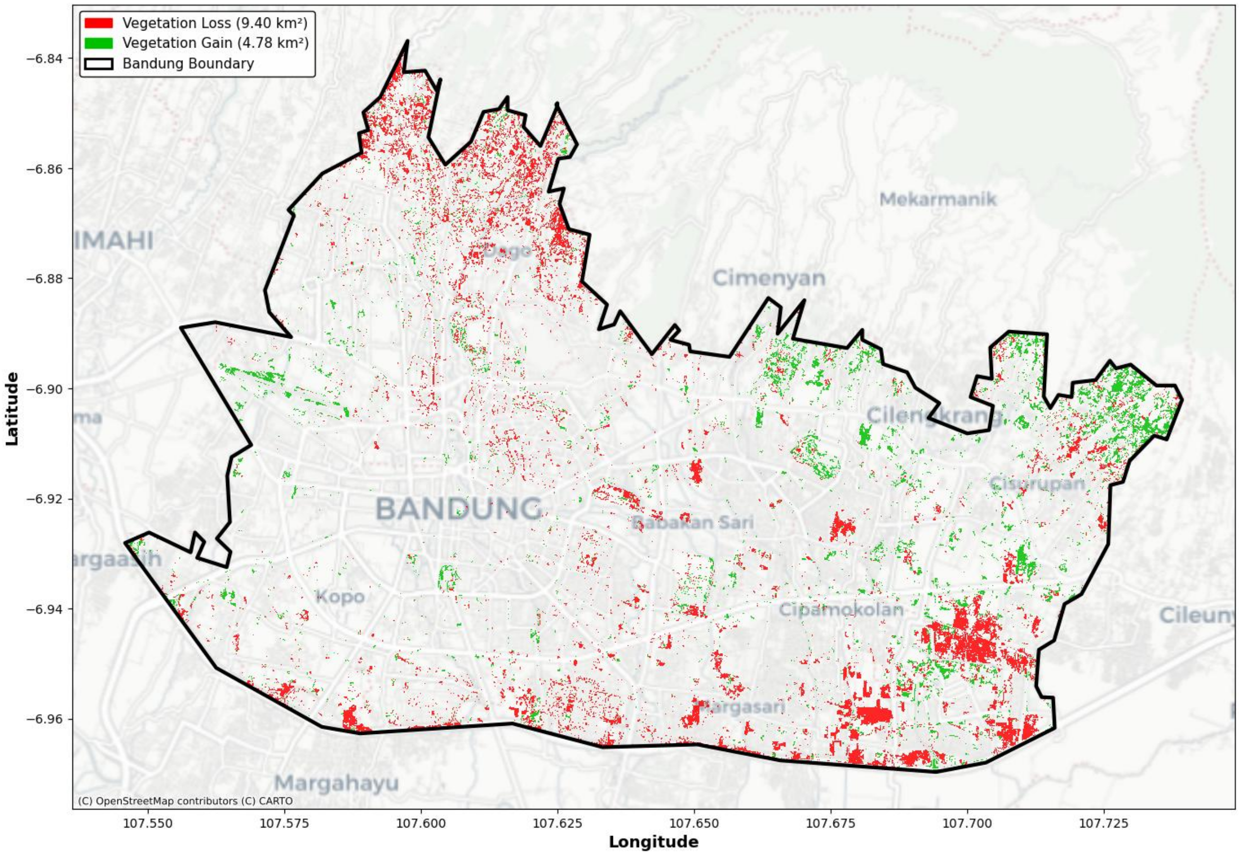

Figure 8. Cumulative Vegetation Change in Bandung (2017-2025)

4. DISCUSSION

4.1 Comparison with Similar Studies in Asian Urban Contexts

One of the clearer conclusions from this study is that RTH policy cannot be implemented the same way across all Indonesian cities. Jakarta and Bandung are at different points along the urbanization spectrum, and the data show that their green-space problems are structurally distinct.

In Jakarta, the central problem is that there is almost no land left to work with. Vegetation fluctuated between roughly 2% and 12% during the study period and settled at 9.3% in 2025. With urban land values as high as they are in the capital, closing a deficit of around 15.80 percentage points — or the 25.63 percentage points recorded at the lowest point in 2023 — is not something that can be achieved through incremental greening alone. Reaching the statutory 30% would realistically require converting underutilized industrial and infrastructural land into parks, reclaiming floodplain corridors, and embedding nature-based solutions into major urban redevelopment projects. Small-scale greening efforts have their place, but they are mathematically insufficient as the primary strategy in a city this built-up.

Bandung's situation, while increasingly serious, is still somewhat more recoverable. Vegetated land remains, particularly in the city outskirt areas, though development pressure there is intense. At this stage, the most effective policy response is preservation, not restoration. Enforcing conversion bans in critical green belts, embedding ecological zoning firmly into spatial plans, and designating strategic green corridors before they are fragmented further would all be more immediately productive than attempting large-scale greening. If current trends continue without intervention, Bandung faces a realistic risk of converging toward Jakarta's condition into a structurally under-greened city where ecological recovery becomes far more expensive and far more difficult with each passing year.

In terms of classification performance, the accuracy levels from this study hold up well against comparable remote sensing work in Asian urban settings. Peralta (2025) reported an OA of 85.71% with a Kappa of 0.779 when applying Random Forest and Sentinel-2 indices in Baguio City, Philippines. Chai et al., (2025) reached 91.4% OA and a Kappa of 0.8119 in a time-series green space mapping study covering Shanghai. Closer to home, Ramadhan and Nugroho (2025) used CART classification on Sentinel-2A data in Tangerang Regency via GEE and reported OA values of 89.36% for 2019 and 90.29% for 2023, roughly placed 4 to 5 percentage points below the mean OA values recorded in this study for both Jakarta (95.47%) and Bandung (94.5%). The consistent advantage of Random Forest over CART in comparable Indonesian settings is also reflected in findings from Khan et al. (2024), who tested four classifiers in GEE for Jammu District, India, and found RF to be the top performer with an OA of 99.36%.

The main classification error in this study which is the confusion between Open Land and either Vegetation or Urban, is not unique to this dataset. The same pattern appears in urban green space mapping studies from Shanghai and Baguio, where misclassification between bare or built-up surfaces and vegetated land remained a persistent challenge (Chai et al., 2025; Joan M. Peralta, 2025). This suggests that such confusion is a systematic limitation of multispectral-only classification at 10 m resolution in rapidly urbanizing tropical and subtropical cities, rather than something specific to this study's methodology weakness. The problem is most acute in transitional zones on the city outskirts, where construction sites, sparsely vegetated lots, and low-density impervious surfaces share similar NIR and SWIR signatures. Integrating SAR data or LiDAR-derived structural features in future work could help resolve these ambiguities, since those data sources carry structural information that is independent of spectral reflectance.

More broadly, the study confirms the value of combining Sentinel-2 imagery, spectral indices, and Random Forest within a cloud-based GEE environment for monitoring urban land-use change. The accuracy results confirm that this setup can generate policy-relevant LULC products for tropical megacities at moderate spatial resolution. At the same time, limitations remain: classification errors exist in every year, systematic field validation was not carried out in this phase, and the satellite-derived vegetation proxy does not map cleanly onto the administrative RTH definitions used in formal planning. These gaps do not invalidate the findings, but they do mean that the outputs are better suited as monitoring indicators than as a direct basis for regulatory enforcement.

4.2 Limitations and Future Work

This study did not explicitly bring in meteorological records, construction permit statistics, or detailed land use policy documents as explanatory variables for the year-to-year fluctuations observed in vegetation extent during 2020–2023, and that is an important limitation of the current work. The interpretation of those fluctuations therefore relies on patterns reported in other studies rather than on a fully coupled dataset for Jakarta and Bandung. Even so, several contextual signals from the wider literature line up closely with what appears in the time series. The 2020 anomaly, when vegetation cover briefly stabilizes or improves slightly in both cities, matches global reports of NDVI recovery during the period of strict COVID-19 mobility restrictions, when reduced human activity and construction slowed direct pressure on urban green spaces (He et al., 2026). The renewed drop in vegetation from 2022 onward coincides with the restart of large-scale construction and the implementation of ATR/BPN Regulation No. 14/2022, which reshaped the national rules for how urban green open space is supplied and used (Kementerian ATR/BPN, 2022). At the same time, park management rules and tree-planting programs introduced by the Jakarta Provincial Government, while encouraging at the policy level, have not yet produced a change in green area large enough to be visible in annual Sentinel-2 composites.

A logical next step is to connect the satellite record more directly to these kinds of additional data. Future research should bring together multiple sources, including BMKG (Badan Meteorologi, Klimatologi, dan Geofisika) rainfall records, BPS (Badan Pusat Statistik) construction statistics, and official RDTR (Rencana Detail Tata Ruang) spatial plan revisions, to better separate the influence of climate variability, formal policy change, and market-driven growth on year-to-year land cover dynamics. Additionally, systematic field validation, supported by very high resolution imagery or LiDAR, would also help resolve ambiguous classes such as sparse vegetation, exposed soil, and low-density built-up areas that tend to overlap spectrally at 10 m resolution. Extending the temporal scope beyond 2025 and adding predictive models would make it possible to explore forward-looking scenarios, for example whether current trends could plausibly lead to 30 percent RTH by 2030 or whether more disruptive interventions will be required to halt and reverse ongoing green space loss.

5. CONCLUSION

This study demonstrates that a machine-learning-based remote sensing workflow leveraging Sentinel-2 imagery and Random Forest classification can effectively characterize land-use and vegetation dynamics in Jakarta and Bandung over the period 2017–2025 and provide actionable insights for Green Open Space (RTH) policy evaluation. Jakarta is shown to be an already heavily urbanized city with vegetation stagnating near 10% of the total land area and remaining far below the 30% RTH benchmark, signaling an ecological deficit that is difficult to fix without transformative land-use reallocation. Bandung, meanwhile, exhibits active sprawl and a rapid erosion of its green space, with the RTH proxy briefly exceeding the statutory 30% threshold in 2020–2021 before collapsing to just 8.52% by 2025, representing a catastrophic decline within less than a decade.

Based on these spatial dynamics, the findings suggest differentiated strategies: aggressive restoration and large-scale nature-based solutions for Jakarta, and urgent preservation and strict control of land conversion on the city's outskirts for Bandung. The study also underscores the importance of integrating remote-sensing-based indicators with systematic field validation and legal definitions of RTH to create monitoring systems that are both scientifically rigorous and administratively credible. More broadly, the workflow presented here offers a replicable GeoAI-based framework that other Indonesian municipalities can adapt to monitor urban land-use change, assess progress toward green-space targets, and support evidence-based spatial planning in the era of rapid urbanization.

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