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ASSESSING URBAN GREENING TRENDS IN ALMATY CITY THROUGH NDVI ANALYSIS OVER FIVE YEARS (2020-2025)

Annotation. This study assesses city-wide urban greening trends in Almaty, Kazakhstan, over a five-year period (June 2020-June 2025) by analyzing seasonal and annual patterns of vegetation using NDVI derived from Sentinel-2 imagery. High-resolution (10 m) Sentinel-2 Level-2A imagery was processed in QGIS, filtered to exclude scenes with cloud coverage ≥30%, and clipped to Almaty's administrative boundaries. NDVI values were calculated for selected cloud-free dates, aggregated at seasonal and custom annual scales (June-May), and statistically analyzed to evaluate spatial and temporal vegetation dynamics. Unlike previous localized studies, this research provides the first city-wide, multi-year assessment of Almaty's urban vegetation using consistent satellite-based NDVI analysis. It establishes a baseline for long-term green infrastructure monitoring and offers valuable insights for sustainable urban planning. The results demonstrate strong, predictable seasonal NDVI patterns aligned with Almaty's continental climate. Summer periods consistently showed peak greenness (~0.50-0.52 NDVI), while winter periods displayed much lower values (~0.01-0.07). No strong or consistent trend in annual mean NDVI was observed, indicating overall stability in city-wide greenness during the study period despite ongoing urban forestry initiatives.
Keywords: Urban greening; NDVI; Sentinel-2; Remote sensing; Almaty city; Vegetation monitoring.

Introduction

Urban green spaces provide essential ecosystem services, enhance environmental quality, and improve the livability of rapidly growing cities. Green infrastructure mitigates urban heat island effects, supports biodiversity, reduces air pollution, and contributes to public health and well-being. For rapidly developing cities such as Almaty – the largest city in Kazakhstan with a population exceeding two million – understanding the dynamics of urban vegetation is critical for sustainable urban planning.

Almaty is situated in a continental climate zone, characterized by hot, dry summers and cold, snowy winters. Rapid urban expansion over recent decades has increased pressure on natural green spaces and driven municipal efforts to enhance urban forestry and green infrastructure. Monitoring the distribution and dynamics of urban vegetation at the city scale is essential for assessing the effectiveness of these initiatives and for informing evidence-based planning and policy.

Remote sensing has emerged as powerful tool for urban vegetation monitoring, offering consistent, repeatable, and large-scale observations. The Normalized Difference Vegetation Index (NDVI), derived from satellite imagery, is a widely used metric for quantifying vegetation health and density. While NDVI has been extensively applied in urban studies to map green spaces and monitor greening trends, challenges remain, particularly in capturing mixed land-cover pixels and in ensuring high temporal consistency across years.

Previous studies in Central Asia and Kazakhstan have applied NDVI analysis to evaluate vegetation dynamics at regional scales, often emphasizing arid and semi-arid environments. However, localized studies in Almaty have largely focused on specific districts or individual green zones rather than providing city-wide, multi-year assessments. Given Almaty's rapid urbanization, climate variability, and policy interest in sustainable planning, there is a clear need for comprehensive monitoring of urban greening trends at the metropolitan scale.

This study aims to address this research gap by providing a city-wide assessment of Almaty's urban vegetation dynamics from June 2020 to June 2025 using Sentinel-2-derived NDVI. By aggregating five years of high-resolution, cloud-filtered satellite imagery, the research analyzes seasonal and annual patterns of urban greenness, identifies stable spatial distributions of green infrastructure, and evaluates potential interannual trends. The findings aim to support urban forestry management, inform planning strategies, and establish a baseline for monitoring future changes in Almaty's urban green spaces.

Research Methods and Materials

The Normalized Difference Vegetation Index (NDVI) is a widely used spectral index derived from remotely sensed imagery to quantify live green vegetation. It is calculated using the reflectance in the near-infrared (NIR) and red (R) bands as $(NIR - R)/(NIR + R)$. NDVI values typically range from -1 to +1, where higher values indicate denser, healthier vegetation (Gao, et al., 2023).

In urban contexts, NDVI is crucial for mapping green spaces, assessing urban heat islands, and informing sustainable city planning (Grover, 2015) (Richards, Global Changes in Urban Vegetation Cover, 2020). Advantages include its simplicity, global availability, and ability to track changes over time. However, NDVI has limitations in urban settings, where mixed pixels can contain vegetation and impervious surfaces, leading to spectral confusion (Neyns, 2022). Shadows, atmospheric effects, and variable spatial resolution can further complicate interpretation (Zhang, 2015).

Remote sensing offers robust tools for urban vegetation monitoring by providing consistent, repeatable, and large-scale observations. Common satellite data sources include Sentinel-2 (10-20 m resolution), Landsat (30 m), and MODIS (250 m-1 km), each offering trade-offs between spatial detail and temporal frequency (Jiang, 2017) (Nouri, 2014).

Numerous studies have applied these data to map urban greening trends. For example, Kuang and Dou investigated 70 major Chinese cities, identifying heterogeneous patterns of greening and browning over two decades (Kuang, 2020). Dutta et al. used hyper-temporal NDVI datasets to analyze long-term trends in Indian cities (Dutta, 2021). Richards and Belcher provided a global assessment of urban vegetation change, highlighting both gains and losses (Richards, 2020).

These precedents demonstrate the value of multi-temporal NDVI analysis for tracking urban green space dynamics, supporting policy decisions, and evaluating greening initiatives (Pan, 2018) (De la Iglesia Martinez, 2023).

In Central Asia, vegetation dynamics have been studied at regional scales, often emphasizing arid and semi-arid environments. Gao et al. assessed NDVI changes across Central Asia from 2001 to 2020, linking trends to climate variability and human activities (Gao, et al., 2023). Berdimbetov et al. analyzed the Aral Sea Basin, demonstrating strong NDVI responses to irrigation and climatic shifts (Berdimbetov, 2021).

Closer to Almaty, studies have examined localized greening projects such as Astana's green belt development using satellite imagery (Driscoll, 2025).

In addition to broader Central Asian assessments, several local studies have focused specifically on Almaty. Kreuzberg examined urban morphology in Tashkent and Almaty, integrating NDVI data to characterize different urban morphotypes within Almaty (Kreuzberg, 2024). This work demonstrates the utility of NDVI for distinguishing urban forms but does not provide a continuous temporal analysis across entire city.

Zengina et al. analyzed geoinformation dynamics of species-diverse urban forest areas in Almaty using GIS and remote sensing techniques (Zengina, 2022). While if offers insights into specific urban forest patches, its focus remains limited to particular green zones without city-wide coverage of multi-year trends.

Kosherbay et al. assessed green zones and urban heat island in Almaty through satellite imagery, applying NDVI to identify spatial patterns of vegetation and heat exposure (Kosherbay, 2022). This study highlights NDVI's relevance for urban climate planning but does not investigate temporal dynamics over multiple years.

Sadyrova et al. provided a detailed ecological assessment of green spaces in Almaty's Bostandyk district, using NDVI to evaluate local vegetation health (Sadyrova, 2023). However, the analysis is restricted to a single administrative area and cannot inform city-scale planning without broader data integration.

Despite the proven utility of NDVI for urban vegetation monitoring, there is a clear research gap in assessing city-wide greening trends in Almaty over multiple years. Given rapid urbanization, climate variability, and policy interest in sustainable planning, understanding the spatiotemporal dynamics of vegetation is critical.

This study addresses that gap by analyzing Sentinel-2 derived NDVI for Almaty from June 2020 to June 2025 at seasonal and annual scales. By aggregating five years of consistent imagery, it aims to provide a robust, city-wide assessment of urban greening patterns, inform local urban forestry and landscape planning, and establish a baseline for monitoring future change.

Almaty is the largest city in Kazakhstan, located in the southeastern part of the country at the foothills of the Tian Shan mountains. Covering approximately 700 km2, it lies at elevations from 600m to over 1000m above sea level. The city experiences a continental climate with hot, dry summers and cold, snowy winters.

Almaty is a rapidly developing urban center with a population exceeding 2 million (Bureau of National Statistics). Rapid urban expansion over recent decades has led to increased pressure on natural green spaces, prompting municipal efforts to expand urban forestry and improve green infrastructure to enhance environmental quality and livability.

This study used Sentinel-2 Level-2A imagery (Copernicus Browser), which provides atmospherically corrected surface reflectance data at 10m resolution. Images were downloaded for the period from June 2020 to June 2025. Necessary spectral bands included the Red (Band 4) and Near-Infrared (Band 8) bands, essential for NDVI computation.

Imagery was selected to minimize cloud cover and ensure consistency across the five-year period. Data were sourced and prepared for processing in QGIS 3.34.15, which supported high-resolution analysis suitable for urban-scale studies.

All Sentinel-2 imagery was imported into QGIS 3.34.15. The administrative boundary of Almaty city was delineated using OpenStreetMap (OSM) layers, providing a precise urban mask. Imagery was clipped to these boundaries to ensure that analysis focused exclusively on the urbanized area.

NDVI was calculated using the QGIS Raster Calculator with the standard formula:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad 1)$$

where NIR corresponds to Band 8 and Red to Band 4 of Sentinel-2 imagery.

Quarterly NDVI composites were generated to reduce noise from single-date variability and cloud contamination. However, final map selection was refined to use the highest-quality cloud-free images available for each season and year, ensuring consistent visual comparison across the study period.

NDVI values were visually inspected for quality, filtered by cloud coverage, and compiled into tabular form for statistical analysis. Data were aggregated at seasonal and annual scales to characterize vegetation dynamics over the five-year period. Mean NDVI and standard deviation were calculated for each season (Winter: Dec-Feb; Spring: Mar-May; Summer: Jun-Aug; Autumn: Sep-Nov) and for each year from 2020 to 2025.

For annual variation analysis, custom analysis years were defined from June to May (e.g. Jun 2020 – May 2021, Jun 2021 – May 2022, Jun 2022 – May 2023) to better capture complete growing cycles without splitting seasonal patterns across calendar years. The final period covered June 2024 through June 2025 due to data availability. Annual averages were calculated to explore potential trends over time; however, no strong or consistent trend was observed.

Spatial analysis was performed in QGIS, generating NDVI maps for representative dates in each season and analysis year to visualize spatial patterns. Higher NDVI values typically indicate denser, healthier vegetation, while lower values reflect urban or barren surfaces. All spatial processing, masking, clipping, and NDVI calculation were performed in QGIS 3.34.15, using its Raster Calculator and vector overlay tools. Administrative boundaries were defined using OpenStreetMap data.

Statistical analysis – including data aggregation and graphical visualization—was performed using Microsoft Excel. This approach facilitates clear, accessible analysis suitable for integration with urban planning and policy discussions.

Research Results

NDVI values were aggregated at seasonal scale over the period from June 2020 to June 2025, excluding all observations with cloud coverage equal to or greater than 30%. Table 1 summarizes seasonal mean NDVI values, standard deviations, and the number of observations for each defined three-month interval.

All NDVI values are reported rounded to two decimal places to reflect typical measurement uncertainty and facilitate interpretation.

Mean NDVI values ranged from approximately 0.01 to 0.52 across seasons and years, with clear differences that align with Almaty's strongly continental climate. Summer periods (June-August) consistently exhibited the highest NDVI values, typically around 0.5-0.52, reflecting peak photosynthetic activity and dense urban vegetation cover during the growing season.

Conversely, winter periods (December-February) showed much lower mean NDVI values, generally between 0.01 and 0.07, corresponding to the dormant phase of most vegetation and reduced photosynthetic activity. These low winter values are characteristic of Almaty's cold, snow-prone winters and limited evergreen planting within the city.

Transitional seasons – spring (March-May) and autumn (September-November) – demonstrated intermediate NDVI values, typically between 0.22 and 0.30, representing the gradual green-up and senescence of vegetation in urban areas. The standard deviations recorded across seasons reflect spatial heterogeneity within the city, with higher variability in transitional periods indicating diverse land cover types and management practices.

Table – 1- Seasonal mean NDVI and standard deviation for Almaty City (June 2020 – June 2025) with cloud coverage <30%

	Season Label	Mean NDVI	Std NDVI	Count
	Jun – Aug 2020	0.51	0.07	17
	Sep – Nov 2020	0.28	0.12	22
	Dec – Feb 2021	0.04	0.02	15
	Mar – May 2021	0.27	0.16	12
	Jun – Aug	0.5	0.06	19

	Season Label	Mean NDVI	Std NDVI	Count
	2021			
	Sep – Nov 2021	0.26	0.14	24
	Dec – Feb 2022	0.07	0.04	15
	Mar – May 2022	0.27	0.18	13
	Jun – Aug 2022	0.5	0.09	20
0	Sep – Nov 2022	0.28	0.14	20
1	Dec – Feb 2023	0.01	0.02	22
2	Mar – May 2023	0.25	0.11	22
3	Jun – Aug 2023	0.52	0.07	19
4	Sep – Nov 2023	0.29	0.1	18
5	Dec – Feb 2024	0.01	0.03	17
6	Mar – May 2024	0.22	0.18	16
7	Jun – Aug 2024	0.52	0.05	17
8	Sep – Nov 2024	0.3	0.16	19
9	Dec – Feb 2025	0.02	0.02	19
0	Mar – May 2025	0.29	0.2	18
1	June 2025	0.5	0.1	4

Note: Complied by the authors based on [21]

These results highlight strong and predictable seasonal variation in urban vegetation greenness in Almaty, consistent with its climate and phenological cycles.

Analysis of seasonal NDVI distributions reveals clear, expected patterns that reflect Almaty's continental climate and urban vegetation dynamics. Figure 1 shows boxplots of NDVI values for each defined seasonal period from June 2020 to June 2025, with all observations filtered to exclude cloud coverage ≥30%.

Summer periods (June-August) consistently displayed the highest NDVI values, with medial values typically around 0.5-0.52, indicating peak photosynthetic activity and full canopy cover in urban vegetation. These high summer NDVI levels are associated with intensive greening in parks, tree-lined streets, and suburban areas.

In contrast, winter periods (December-February) showed markedly lower NDVI values, with median often around 0.01-0.07, reflecting dormant vegetation, leaf-off conditions, and minimal photosynthetic activity due to cold temperatures and snow cover.

Spring (March-May) and autumn (September-November) exhibited intermediate NDVI distributions, with median values approximately 0.22-0.3. These transitional seasons capture the processes of green-up and senescence, respectively, as urban vegetation responds to changing temperature and daylight conditions.

The boxplots also highlight the intra-seasonal variability of NDVI, as shown by interquartile ranges and the presence of outliers. Variability tends to be higher in transitional seasons, likely reflecting spatial heterogeneity in land cover types, varying planting strategies, and differential irrigation practices across the city.

To ensure full transparency and reproducibility of this analysis, the complete filtered NDVI observation dataset used for seasonal and annual calculations is provided below.

The dataset includes Sentinel-2 derived NDVI values for Almaty City from June 2020 to June 2025, with all scenes filtered to exclude cloud coverage equal to or greater than 30%. Each record includes the observation date, calculated NDVI value, cloud coverage percentage, and assigned seasonal label (NDVI Observation Dataset for Almaty City (June 2020–June 2025)) (Copernicus Browser).

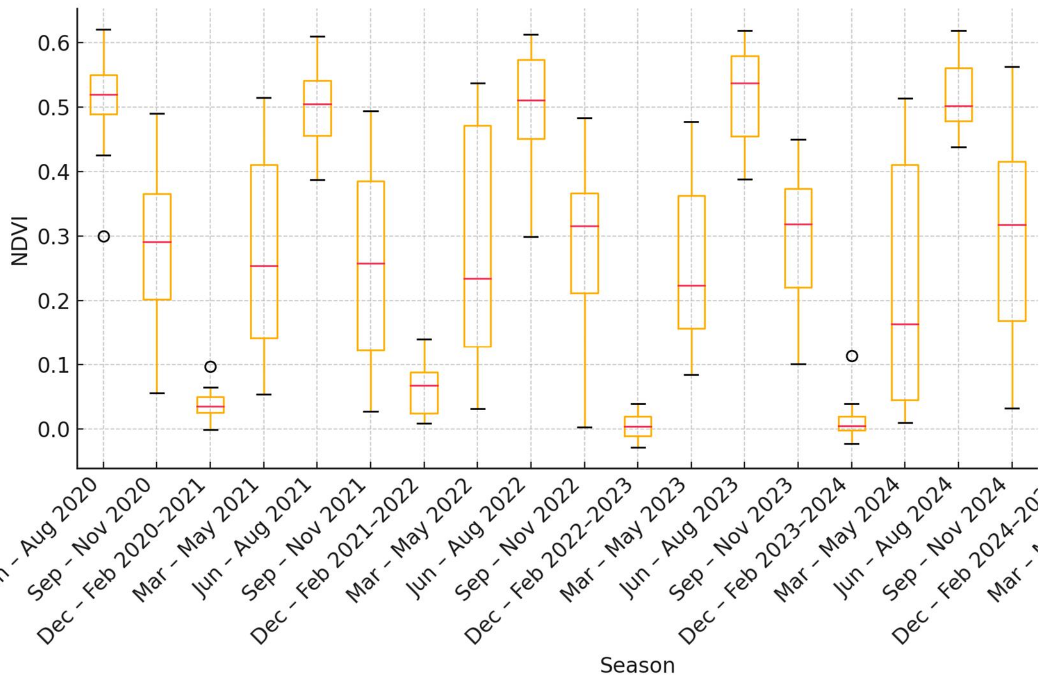

Figure - 1 - Seasonal NDVI distribution in Almaty (June 2020 – June 2025) with cloud coverage <30%. Complied by the authors based on [21]

These seasonal patterns are consistent with expectations for Almaty's climate and provide important context for interpreting urban vegetation dynamics.

Annual mean NDVI values were also calculated for each custom analysis year (June-May) to examine potential interannual trends in urban greenness. While minor year-to-year differences were observed, no strong or consistent trend was evident over the five-year study period. This suggests that short-term NDVI variability in Almaty is primarily driven by seasonal and spatial patterns rather than clear long-term changes in overall urban vegetation cover.

Although the main analysis did not identify a strong or consistent monotonic trend over this five-year period, Table 2 summarizes the mean NDVI, standard deviation, and number of observations for each annual period.

Table – 2 - Annual mean NDVI and standard deviation for Almaty City (June 2020 – June 2025) with cloud coverage <30%, by custom June–May years

	Analysis Year	Mean NDVI	Std NDVI	Count
	Jun 2020 – May 2021	0.275	0.0925	66
	Jun 2021 – May 2022	0.275	0.105	71
	Jun 2022 – May 2023	0.26	0.09	84
	Jun 2023 – May 2024	0.26	0.0975	70
	Jun 2024 – Jun 2025	0.326	0.106	77

Note: Note: Complied by the authors based on [21]

To visualize spatial patterns of urban vegetation in Almaty, NDVI maps were generated from Sentinel-2 L2A imagery (Copernicus Browser) captured at carefully selected dates across multiple years and seasons. Each image provides a high-resolution, spatially explicit visualization of urban vegetation cover. Figures from 2 to 7 present representative NDVI maps of Almaty City spanning the study period from 2020 to 2025.

Figure - 2. Representative NDVI maps of Almaty City for June, September, November 2020. Sentinel-2 L2A NDVI composites with cloud coverage <30%. Note: Complied by the authors based on [3; 21]

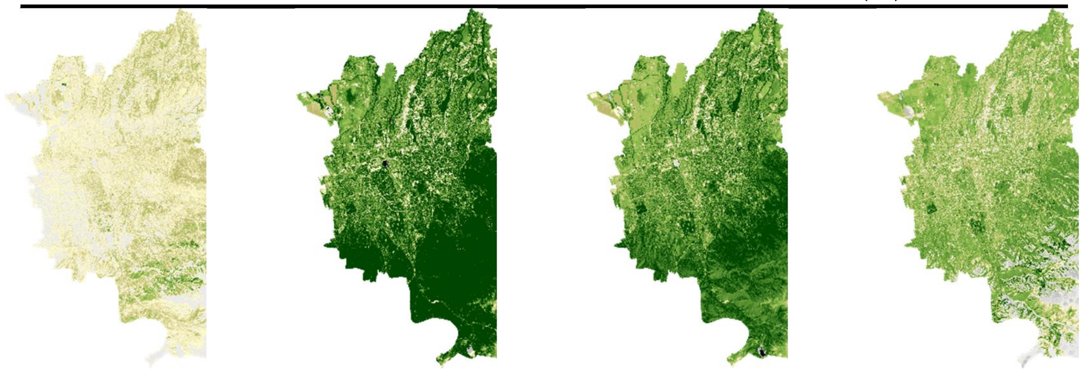

Figure - 3. Representative NDVI maps of Almaty City for March, June, September, December 2021. Sentinel-2 L2A NDVI composites with cloud coverage <30%. Note: Complied by the authors based on [3; 21]

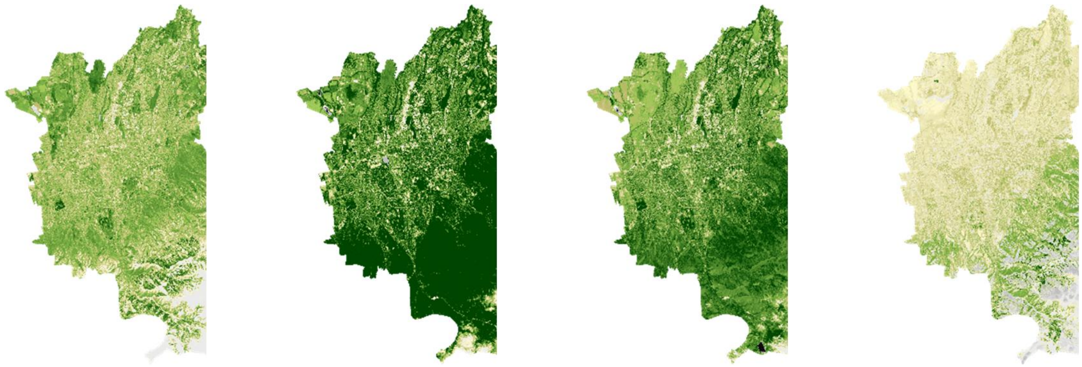

Figure - 4. Representative NDVI maps of Almaty City for March, June, September, December 2022. Sentinel-2 L2A NDVI composites with cloud coverage <30%. Note: Complied by the authors based on [3; 21]

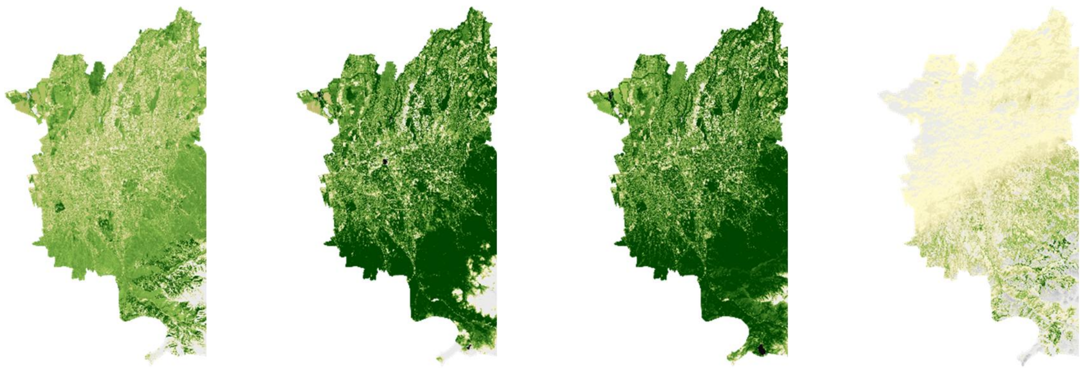

Figure - 5. Representative NDVI maps of Almaty City for March, June, September, December 2023. Sentinel-2 L2A NDVI composites with cloud coverage <30%. Note: Complied by the authors based on [3; 21]

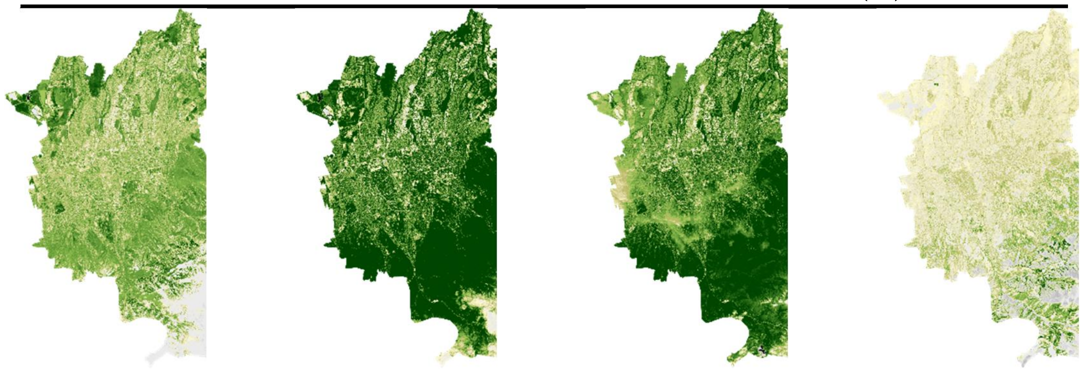

Figure - 6. Representative NDVI maps of Almaty City for March, June, September, December 2024. Sentinel-2 L2A NDVI composites with cloud coverage <30%. Note: Complied by the authors based on [3; 21]

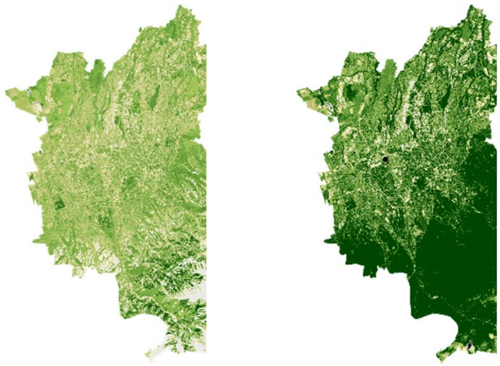

Figure - 7. Representative NDVI maps of Almaty City for March, June 2025. Sentinel-2 L2A NDVI composites with cloud coverage <30% Note: Complied by the authors based on [3; 21]

Across the entire five-year timeframe, the maps consistently reveal strong and predictable seasonal patterns. Summer images show widespread high NDVI values, indicating peak vegetation vigor in parks, suburban residential areas, and the forested foothills south of the city. In contrast, winter maps demonstrate uniformly low NDVI values, reflecting seasonal dormancy and potential snow cover in the surrounding mountains. Spring and autumn maps show transitional phases, with moderate NDVI values as vegetation emerges from or enters dormancy.

Importantly, despite interannual variability in weather and local management practices, the overall spatial patterns of urban greening appear highly stable. High NDVI consistently clusters in green infrastructure such as parks, river corridors, and peri-urban forests, while the dense urban core exhibits persistently lower NDVI values due to impervious surfaces and sparse canopy cover.

This consistent spatial heterogeneity highlights the structured distribution of urban green spaces within Almaty, underlining the importance of maintaining and expanding vegetated areas to enhance urban resilience and livability. The maps serve as an essential complement to temporal trend analyses, offering clear visual evidence of the city’s green infrastructure network and its seasonal dynamics.

This study provides a city-wide assessment of urban vegetation dynamics in Almaty over a five-year period (June 2020 – June 2025) using Sentinel-2-deerived NDVI. Results reveal strong and predictable seasonal variations in urban greenness, with peak NDVI values consistently observed during the summer months (June-August) and much lower values during winter (December-February). These patterns align with Almaty's continental climate, which features hot, dry summers and cold, snow-prone winters that limit photosynthetic activity.

The clear seasonal cycles detected here are consistent with other regional and global studies. For example, Gao et al. (2023) found NBVI seasonality across Central Asia closely linked to climatic variability and water availability. Similarly, Zengina et al. (2022) demonstrated the value of remote sensing for capturing urban forest dynamics within Almaty, though their focus was limited to species-diverse patches rather than city-wide trends.

Our results add new insight by providing continuous, standardized NDVI observations at seasonal intervals for the entire urban extent of Almaty. Unlike previous localized studies (e.g. Sadyrova et al., 2023; Kosherbay et al., 2022), this analysis applies consistent methodology across multiple years, enabling direct comparison of seasonal and interannual patterns. The strong stability observed in spatial NDVI patterns – where parks, suburban green belts, and foothill forests consistently exhibit high NDVI while the dense urban core remains lower – underscores the structured distribution of green infrastructure in the city.

Notably, while seasonal patterns were robust, annual averages revealed no strong or consistent monotonic trend over the five-year study period. This suggests that, despite policy interest in expanding urban greening, observable NDVI-based gains at the city scale may be limited or slow to emerge over short periods. It also highlights the importance of sustained, multi-year monitoring to detect longer-term trajectories and evaluate the effectiveness of urban forestry initiatives.

There are several important limitations to consider. The analysis relied on optical imagery filtered for cloud coverage below 30%, which limited data availability in some months and may introduce sampling bias toward clearer, drier periods. The five-year timeframe, while useful for establishing baseline conditions, may be too short to capture gradual greening trends or structural changes in urban vegetation. NDVI itself, while widely used, is sensitive to mixed pixels, shadows, and atmospheric conditions, particularly in complex urban environments (Neyns, 2022).

Despite these limitations, this study demonstrates the value of Sentinel-2 imagery and NDVI analysis for city-scale urban green space monitoring in Almaty. The generated seasonal composites and spatial maps can inform urban planning by identifying consistent green infrastructure patterns and highlighting areas with low vegetation cover. For policymakers, these results underline the need for targeted planting strategies, maintenance of existing green spaces, and integration of remote sensing data into planning workflows.

Future research could extend this work by incorporating higher-resolution imagery (e.g. PlanetScope), multi-sensor fusion, or land cover classification to distinguish tree canopy, grasslands, and impervious surfaces. Additionally, longer time series would help evaluate the impact of specific urban greening programs, policy interventions, and climate variability on the city's green infrastructure over time.

Conclusion

This study provides a comprehensive, city-wide assessment of urban vegetation dynamics in Almaty over a five-year period (June 2020-June 2025) using Sentinel-2-derived NDVI. By aggregating and analyzing high-resolution satellite imagery filtered for cloud coverage below 30%, the research captures clear seasonal patterns of urban greenness consistent with Almaty's continental climate.

Summer periods consistently exhibited the highest NDVI values, reflecting peak vegetation vigor and highlighting the importance of urban parks, green corridors, and foothill forests in maintaining city-wide green infrastructure. In contrast, winter maps showed uniformly low NDVI values, underscoring the strong seasonality of Almaty's vegetation and the challenges posed by cold, snow-prone conditions.

Importantly, while the analysis revealed robust seasonal cycles and stable spatial patterns of urban green space distribution, no strong or consistent monotonic trend in annual average NDVI was observed over the study period. This suggests that observable city-scale greening efforts may be incremental or too recent to produce detectable NDVI changes within a five-year timeframe.

These findings underline the value of consistent, multi-year remote sensing monitoring for urban planning and green infrastructure management. The study establishes a critical baseline for assessing future greening initiatives and urban forestry policies in Almaty. Continued monitoring, combined with higher-resolution data and land cover classification approaches, will be essential for evaluating the long-term effectiveness of urban greening strategies and for supporting evidence-based planning aimed at enhancing urban resilience and livability.

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АЛМАТЫ ҚАЛАСЫНДАҒЫ КӨГАЛДАНДЫРУ ҮРДІСТЕРІН NDVI ТАЛДАУЫ АРҚЫЛЫ БЕС ЖЫЛДЫҚ КЕЗЕҢДЕ (2020-2025 ЖЖ.) БАҒАЛАУ

Аңдатпа. Бұл зерттеуде Sentinel-2 деректері бойынша есептелген NDVI пайдалана отырып, өсімдіктердің маусымдық және жылдық өзгерістерін талдау арқылы бес жылдық кезеңдегі (2020 жылғы маусым – 2025 жылғы маусым) Алматыдағы (Қазақстан) Қалалық көгалдандыру үрдістері бағаланады. QGIS-те Sentinel-2 Level-2A суреттерінің жоғары кеңістіктік ажыратымдылығы (10 м) өңделді: ≥30% бұлтты көріністер алынып тасталды, ал суреттер Алматының әкімшілік шекаралары бойынша кесілді. NDVI мәндері таңдалған бұлтсыз күндер үшін есептелді, маусымдар мен арнайы белгіленген жылдық кезең (Маусым-Мамыр) бойынша біріктірілді және өсімдіктердің кеңістіктік және уақыттық динамикасын бағалау үшін статистикалық талдаудан өтті. Алдыңғы жергілікті зерттеулерден айырмашылығы, бұл жұмыс NDVI сериялық спутниктік талдау негізінде Алматының көгалдандыруын алғашқы қалалық көпжылдық бағалау болып табылады. Бұл жасыл инфрақұрылымды ұзақ мерзімді бақылау үшін негіз қалауға мүмкіндік береді және тұрақты қала құрылысы үшін құнды деректер береді. Нәтижелер Алматының континенттік климатына сәйкес келетін NDVI нақты және болжамды маусымдық үлгілерін көрсетеді. Жазғы кезеңдер NDVI максималды мәндерін тұрақты түрде көрсетті (~0.50-0.52), ал қысқы кезеңдер айтарлықтай төмен мәндермен сипатталды (~0.01-0.07). Зерттеу кезеңінде орташа жылдық NDVI өзгеруінің айқын немесе тұрақты тенденциясы анықталған жоқ, бұл қалалық жасыл инфрақұрылымды дамыту жөніндегі бастамалардың жалғасуына қарамастан, қаланың көгалдандыру деңгейінің жалпы тұрақтылығын көрсетеді.

Кілт сөздер: Қаланы көгалдандыру; NDVI; Sentinel-2; Қашықтықтан зондтау; Алматы; Өсімдікті мониторингілеу.

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ОЦЕНКА ТЕНДЕНЦИЙ ОЗЕЛЕНЕНИЯ ГОРОДА АЛМАТЫ НА ОСНОВЕ АНАЛИЗА NDVI ЗА ПЯТЬ ЛЕТ (2020-2025 ГГ.)

Аннотация. В данном исследовании оцениваются городские тенденции озеленения в Алматы (Казахстан) за пятилетний период (июнь 2020 г.-июнь 2025 г.) путем анализа сезонных и годовых изменений растительности с использованием NDVI, рассчитанного по данным Sentinel-2. Высокое пространственное разрешение (10 м) снимков Sentinel-2 Level-2A было обработано в QGIS: сцены с облачностью ≥30 % были исключены, а изображения обрезаны по административным границам Алматы. Значения NDVI рассчитывались для выбранных безоблачных дат, агрегировались по сезонам и специально определённым годовому периоду (Июнь-Май) и подвергались статистическому анализу для оценки пространственной и временной динамики растительности. В отличие от предыдущих локальных исследований, данная работа представляет собой первую городскую многолетнюю оценку озеленения Алматы на основе последовательного спутникового анализа NDVI. Это позволяет заложить базу для долгосрочного мониторинга зеленой инфраструктуры и даёт ценные данные для устойчивого городского планирования. Результаты демонстрируют чёткие и предсказуемые сезонные модели NDVI, соответствующие континентальному климату Алматы. Летние периоды стабильно показывали максимальные значения NDVI (~0.50-0.52), тогда как зимние периоды характеризовались значительно более низкими значениями (~0.01-0.07). В течение исследуемого периода не выявлено выраженной или стабильной тенденции изменения среднегодового NDVI, что указывает на общую стабильность уровня озелененности города, несмотря на продолжающиеся инициативы по развитию городской зелёной инфраструктуры.

Ключевые слова: Озеленение города; NDVI; Sentinel-2; Дистанционное зондирование; Алматы; Мониторинг растительности.