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Ilkhomjon Abdullaev[1], **Lola Gulyamova**[2], **Nargiza Abdullaeva**[3],
Sattarbergan Avezov[4], **Abdujalil Muminov**[5], **Tumaris Ramanova**[6]

ASSESSMENT OF LAND SURFACE TEMPERATURE DYNAMICS IN TASHKENT (2000–2024): A SPATIOTEMPORAL ANALYSIS BASED ON SATELLITE DATA

ABSTRACT

Urbanization alters the thermal characteristics of cities and amplifies the Urban Heat Island (UHI) effect, which has implications for environmental sustainability and human well-being. This study analyzes the spatiotemporal variability of Land Surface Temperature (LST) in Tashkent, Uzbekistan, between 2000 and 2024 using multi-temporal Landsat imagery and geospatial techniques in ArcGIS Pro. LST and the Normalized Difference Vegetation Index (NDVI) were extracted to evaluate thermal dynamics and vegetation changes across the city's 12 administrative districts. The results indicate a persistent increase in LST over the 24-year period, with maximum intensification in the central and eastern districts, particularly Mirabad, Yashnabad, and Shaykhontohur. Concurrently, NDVI values declined across most districts, reflecting substantial vegetation loss, especially in urban cores characterized by dense built-up areas. In contrast, peripheral districts such as Bektemir and Yangihayot remained relatively cooler, underscoring the role of vegetation and lower construction density in regulating surface heat. Correlation analysis confirmed a strong inverse relationship between LST and NDVI, emphasizing the importance of urban green cover in mitigating thermal stress. These findings highlight the need for evidence-based urban planning strategies, including green infrastructure development and vegetation restoration, to reduce heat exposure and enhance climate resilience in rapidly expanding dryland cities such as Tashkent.

KEYWORDS: Land Surface Temperature, Normalized Difference Vegetation Index, spatiotemporal analysis, urban heat hotspots, climate-resilient urban planning

INTRODUCTION

Rapid urbanization is reshaping terrestrial landscapes worldwide, particularly in emerging economies where demographic growth and infrastructure expansion often advance more rapidly

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[1] National University of Uzbekistan named after Mirzo Ulugbek, 4, Universitetskaya str., Tashkent, 100174, Uzbekistan, *e-mail:* **ilkhomjon.abdullaev@gmail.com**

[2] Tashkent State Technical University named after Islam Karimov, 2, Universitetskaya str., Tashkent, 100174, Uzbekistan, *e-mail:* **lolagulyam@gmail.com**

[3] Tashkent State Technical University named after Islam Karimov, 2, Universitetskaya str., Tashkent, 100174, Uzbekistan, *e-mail:* **abdullaeva.nargiza@tdtu.uz**

[4] Urgench State University named after Abu Rayhan Biruni, 14, Kh. Alimdjana str., Tashkent, 220100, Uzbekistan, *e-mail:* **avezovsattarbergan@gmail.com**

[5] Alfraganus University, 2a, Yukori Karakamish str., Tashkent, 100190, Uzbekistan, *e-mail:* **muminov010@gmail.com**

[6] National University of Uzbekistan named after Mirzo Ulugbek, 4, Universitetskaya str., Tashkent, 100174, Uzbekistan, *e-mail:* **tumarisramanova@mail.ru**

than environmental regulations or planning frameworks can adapt. Among the many environmental consequences of urban growth, the intensification of the Urban Heat Island (UHI) effect has received considerable scientific attention. The UHI effect describes the tendency of urbanized regions to exhibit significantly higher air and surface temperatures compared to adjacent rural or peri-urban zones, largely due to anthropogenic modifications of the land surface [*Voogt*, *Oke*, 2003]. Impervious construction materials, including asphalt, concrete, and rooftops, exhibit both high thermal inertia and low albedo, which together enhance the absorption of solar radiation during the day and prolong the retention of heat at night. This process disrupts local energy balances, modifies urban microclimates, elevates energy consumption for cooling, worsens ambient air quality, and heightens exposure to heat-related health risks [*Weng*, 2009].

A fundamental parameter for monitoring and assessing urban thermal environments is Land Surface Temperature (LST). LST provides a direct indicator of surface-level heat dynamics and reflects the cumulative influence of land cover type, vegetation density, and built-up infrastructure. With the increasing availability of satellite-based thermal infrared imagery, it has become possible to systematically monitor LST variations across large geographic extents and extended temporal intervals. Multispectral and thermal sensors onboard platforms, such as Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI/TIRS provide valuable datasets that enable researchers to evaluate spatiotemporal dynamics of LST, identify persistent urban heat hotspots, and assess the cooling effects of green infrastructure [*Sobrino* et al., 2004; *Imhoff* et al., 2010; *Li* et al., 2013]. These tools have proven indispensable for urban climate studies, particularly in data-scarce regions where ground-based observations are sparse or inconsistent.

Vegetation plays an especially critical role in regulating surface thermal conditions by providing shading, enhancing evapotranspiration, and reducing direct heat accumulation. The Normalized Difference Vegetation Index (NDVI), derived from reflectance values in the red and near-infrared spectral bands, is widely used as a proxy for vegetation health, vigor, and density. Numerous empirical studies across different climate zones have consistently demonstrated an inverse relationship between NDVI and LST, whereby vegetated areas are associated with lower surface temperatures compared to built-up or barren areas [*Buyantuyev*, *Wu*, 2010; *Zhou* et al., 2014]. In arid and semi-arid environments, such as those characterizing much of Central Asia, this relationship becomes particularly pronounced. Scarcity of vegetation combined with high solar radiation and low soil moisture renders the land surface highly sensitive to land-use and land-cover changes, thereby magnifying the consequences of vegetation loss for urban thermal regimes [*Rasul* et al., 2018].

Tashkent, the capital of Uzbekistan and the largest urban center in Central Asia, provides a compelling case study for analyzing LST dynamics in the context of UHI formation. Over the past two decades, the city has undergone rapid population growth, industrial expansion, and urban sprawl. Between 2000 and 2024, Tashkent's built-up area expanded substantially, often at the expense of peri-urban agricultural lands, tree plantations, and other forms of green space. The resulting decline in vegetation cover has likely exacerbated surface warming and contributed to the emergence of localized heat islands. Despite this transformation, comprehensive longitudinal assessments of surface temperature dynamics in Tashkent remain limited, with most prior studies focusing on short time frames or restricted spatial coverage.

Recent localized research has highlighted the ecological and climatic functions of urban vegetation in Tashkent. For example, green infrastructure elements such as parks, tree-lined boulevards, and urban forests have been shown to measurably reduce surface temperatures in densely built-up areas, providing tangible benefits for thermal comfort and heat risk reduction [*Sharipov*, *Khayitmurodov*, 2024]. Nevertheless, these studies are often constrained by narrow datasets, focusing either on individual neighborhoods or on short-term observations, which limits their ability to capture long-term trends or inform citywide urban planning strategies. To effectively support sustainable urban management and climate adaptation in Tashkent, a district-scale, longitudinal analysis of LST and vegetation cover is urgently required.

The present study addresses this gap by conducting a spatiotemporal analysis of LST dynamics in Tashkent from 2000 to 2024 using multi-temporal Landsat imagery and advanced geospatial processing in ArcGIS Pro. Six benchmark years (2000, 2005, 2010, 2015, 2020, and 2024) were selected to provide an evenly distributed temporal dataset, enabling the identification of long-term trends in both surface temperature and vegetation cover. LST was retrieved from thermal infrared bands and corrected for emissivity using established radiative transfer models [*Sobrino* et al., 2004; *Zhao-Liang* et al., 2013; *Oppong*, 2024]. NDVI was derived from multispectral reflectance data to evaluate vegetation distribution and change. All datasets were georeferenced and analyzed at the scale of Tashkent's 12 administrative districts, thereby facilitating district-level comparisons and zonal statistical assessments of spatial disparities in surface heat exposure.

The methodological framework adopted in this study builds upon recent advances in remote sensing and GIS-based environmental modeling. Prior research has demonstrated the analytical value of integrating thermal imagery, vegetation indices, and land-use classifications for assessing urban heat distribution in dryland cities [*Jenerette* et al., 2011; *Rasul* et al., 2018]. In the Central Asian context, GIS-based cadastral and land-monitoring systems are increasingly being incorporated into municipal governance, providing new opportunities for evidence-based urban planning [*Abdullaev* et al., 2022; 2023]. By employing ArcGIS Pro for all image processing, classification, and visualization tasks, this study ensures methodological rigor, reproducibility, and compatibility with broader geospatial decision-support frameworks.

The objectives of this study are to complete the following using a geospatial approach:

- quantify the long-term spatiotemporal trends in land surface temperature across Tashkent between 2000 and 2024;
- analyze the statistical relationship between LST and vegetation cover using NDVI as a proxy;
- identify intra-urban disparities in thermal conditions across the city's 12 administrative districts;
- develop evidence-based recommendations for incorporating green infrastructure into urban planning to mitigate UHI effects and enhance climate resilience.

By investigating the LST-NDVI relationship across multiple temporal points and spatial units, this study contributes to both theoretical and applied research on climate-resilient urban design in dryland regions. The findings are expected to inform not only academic debates but also practical policy interventions in environmental planning, infrastructure development, and public health adaptation. More broadly, the results will provide valuable insights for other rapidly urbanizing cities in Central Asia that face similar climatic constraints and urbanization pressures.

RESEARCH MATERIAL AND METHODS

Research area

This study was conducted in Tashkent, the capital of Uzbekistan and the largest metropolitan area in Central Asia. Geographically, the city is located at approximately 41.31°N latitude and 69.28°E longitude, within a semi-arid continental climate zone that is characterized by hot, dry summers and cold winters. Positioned in the northeastern part of the country, Tashkent lies in the foothills of the western Tien Shan mountains, with elevations ranging from 407 to 480 meters above sea level. The city's geographic location and topographic setting make it particularly susceptible to climatic extremes and land surface modifications.

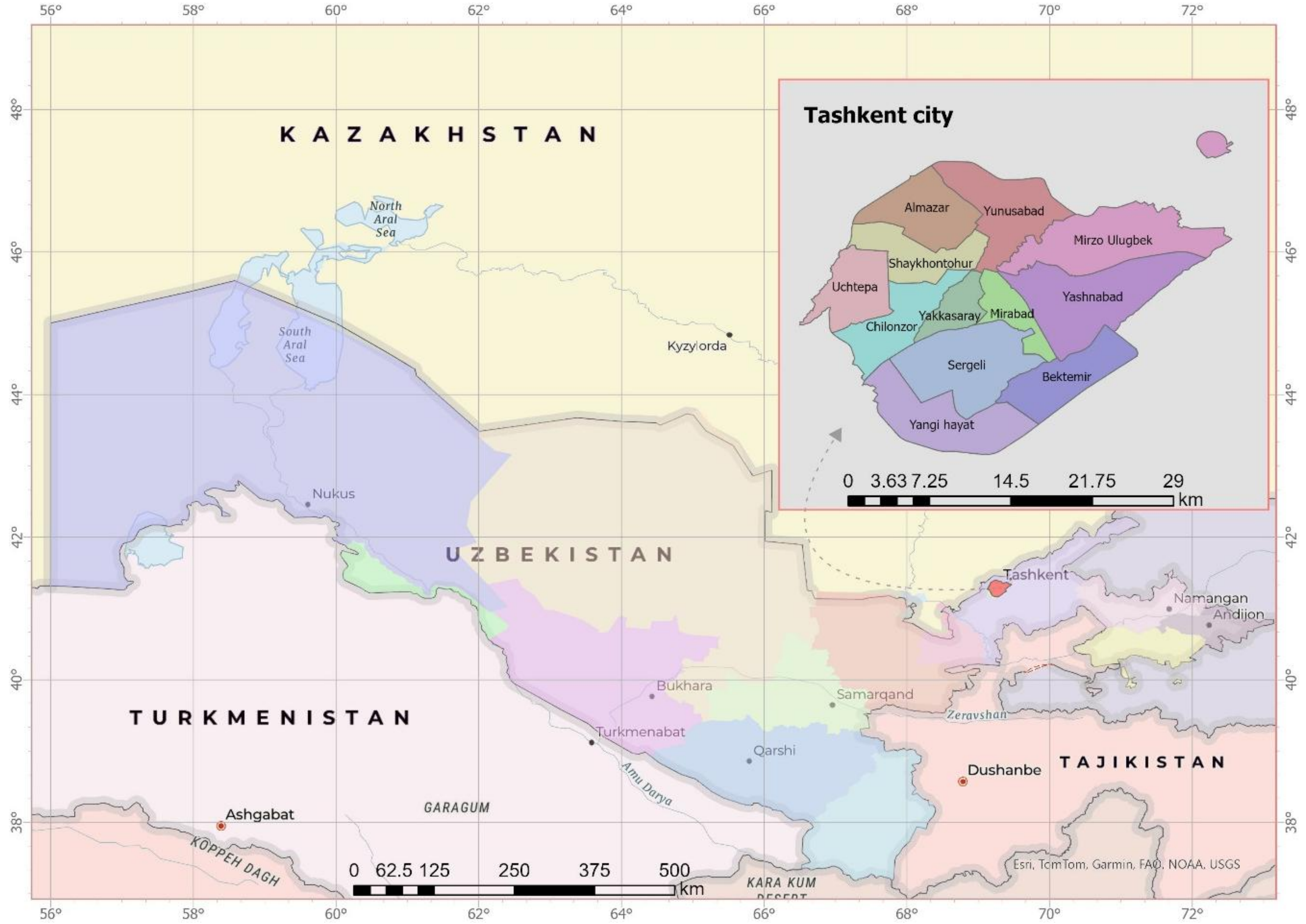

Fig. 1. Location of the Tashkent Region

Administratively, Tashkent encompasses an area of approximately 360 km² and is divided into 12 districts: Shaykhontohur, Uchtepa, Chilonzor, Yakkasaray, Mirabad, Yunusabad, Mirzo Ulugbek, Yashnabad, Sergeli, Bektemir, Almazar, and Yangihayot (Fig. 1). These districts exhibit considerable variation in terms of demographic density, land-use configurations, urban infrastructure, and vegetation cover, thereby providing a heterogeneous landscape that is well-suited for assessing spatial disparities in urban heat exposure.

Over the past two decades, Tashkent has undergone rapid urban transformation, fueled by demographic growth (surpassing 3.1 million residents by 2025), economic liberalization, and extensive infrastructural modernization. The conversion of agricultural fields and vegetated areas into impervious built-up surfaces has significantly reduced ecosystem services, particularly those related to natural microclimate regulation and temperature moderation. This shift underscores the ecological costs of rapid urbanization and highlights the urgency of climate-responsive planning.

The city is especially relevant for urban climate research due to its accelerated land-use change, limited natural vegetation cover, and recurrent exposure to extreme summer heat, when daytime land surface temperatures frequently exceed 40 °C. Such conditions not only intensify the Urban Heat Island (UHI) effect but also exacerbate energy demand and heat-related health risks.

To address these challenges, this study employs a spatially explicit framework based on multi-temporal satellite remote sensing. Analyses are conducted at two complementary levels: (i) a raster-based pixel-level assessment, which captures fine-grained variations in Land Surface Temperature (LST) and the Normalized Difference Vegetation Index (NDVI); and (ii) an aggregated district-level analysis, which facilitates the interpretation of spatial heterogeneity across administrative units and supports evidence-based decision-making. This dual-scale approach allows for the identification of localized thermal hotspots while also providing actionable insights for municipal climate adaptation strategies between 2000 and 2024.

Materials and methods

This study investigates the spatial and temporal dynamics of urban heat in Tashkent over a 24-year period (2000–2024) through the combined use of satellite remote sensing and advanced geospatial analysis in ArcGIS Pro. The primary focus is the relationship between Land Surface Temperature (LST) and vegetation cover, with particular attention to how changes in urban morphology influence thermal conditions. A multi-temporal dataset of Landsat imagery was employed, encompassing six benchmark years (2000, 2005, 2010, 2015, 2020, and 2024). These years were strategically selected to provide an evenly distributed temporal sequence, allowing the identification of both gradual long-term trajectories and episodic fluctuations in urban thermal dynamics.

Satellite imagery was obtained from the United States Geological Survey (USGS) Earth Explorer platform, which offers comprehensive access to global Landsat archives. Three generations of Landsat sensors were utilized: Landsat-5 Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+), and Landsat-8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS). The integration of these datasets ensured continuity in spatial resolution, radiometric quality, and spectral comparability across the study period. To minimize atmospheric interference and seasonal variability, imagery was restricted to the summer months (June–August), when land surface heating is most pronounced and UHI effects are most evident. Only scenes with less than 10 % cloud cover were retained to guarantee robust extraction of both thermal and spectral indices.

In addition to satellite imagery, vector-based spatial boundary data were incorporated to contextualize the analysis. Official district-level administrative shapefiles were obtained from the open data portal of the city of Tashkent. These boundaries provided a spatial framework for aggregating pixel-level LST and NDVI values, enabling zonal statistics and inter-district comparisons. The integration of raster and vector datasets established a comprehensive empirical foundation for evaluating the spatiotemporal evolution of urban heat, thereby supporting both localized diagnostics and city-wide assessments of heat distribution (Table 1).

Table 1. Data sources for spatiotemporal assessment of urban heat dynamics in Tashkent (2000–2024)

Data Type	Sensor/ Source	Date acquired	Purpose	Source
Satellite Imagery	Landsat-5 TM	2000.07.28	LST and NDVI analysis (baseline period)	USGS Earth Explorer[1]
Satellite Imagery	Landsat-7 ETM+	2005.07.26 2010.07.24	LST and NDVI analysis (mid-period)	USGS Earth Explorer
Satellite Imagery	Landsat-8 OLI/TIRS	2015.07.30 2020.07.27 2024.07.22	LST and NDVI analysis (recent period)	USGS Earth Explorer
Spatial Boundary Data	Tashkent District Shapefiles	All years	Zonal aggregation and district-level mapping of indices	Open Data Portal of Tashkent[2]

All satellite imagery was preprocessed within ArcGIS Pro to ensure consistency and analytical accuracy. Preprocessing steps included projection to the World Geodetic System 1984 (WGS 84), Universal Transverse Mercator (UTM) Zone 42N coordinate system, radiometric calibration of raw digital numbers, and clipping to the official administrative boundary of Tashkent. For district-level assessments, a shapefile delineating the city's 12 administrative units (Yangihayot, Bektemir, Uchtepa, Chilonzor, Yakkasaray, Shaykhontohur, Yunusabad, Almazar, Mirabad, Sergeli, Yashnabad, and Mirzo Ulugbek) was incorporated as the primary vector layer.

Land Surface Temperature (LST) was retrieved from the thermal infrared bands of each Landsat sensor following a standardized five-step procedure:

1. **Conversion of digital number (DN) values to top-of-atmosphere (TOA) radiance.**

For Landsat-5 TM and Landsat-7 ETM+:

$$L_\lambda = \frac{(L_{max} - L_{min})}{(QCAL_{max} - QCAL_{min})}(DN - QCAL_{min}) + L_{min} \quad (1),$$

and for Landsat-8 OLI/TIRS:

$$L_\lambda = M_L \times Q_{cal} + A_L \quad (2),$$

where L_λ — TOA spectral radiance (W / m² · sr · μm),
M_L and A_L — radiance rescaling factors,
Q_{cal} — the quantized pixel value.

2. **Conversion of TOA radiance to brightness temperature (BT) in Kelvin.**

$$T_B = \frac{K_2}{ln(\frac{K_1}{L_\lambda} + 1)} \quad (3),$$

where T_B — brightness temperature; K_1 and K_2 — band-specific thermal calibration constants provided in the metadata.

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[1] Web resource: https://earthexplorer.usgs.gov/ (accessed 07.07.2025)

[2] Web resource: https://opendata.tashkent.uz/ (accessed 08.08.2025)

3. Estimation of vegetation index (NDVI).

NDVI was derived as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{4},$$

where

- for Landsat 5:
  NIR = Band 4,
  RED = Band 3;
- for Landsat 8:
  NIR = Band 5,
  RED = Band 4.

4. Estimation of land surface emissivity (LSE).

The proportion of vegetation (PV) was calculated as:

$$PV = (\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}})^2 \tag{5},$$

and emissivity was then estimated as:

$$\varepsilon = 0.004 \cdot PV + 0.986 \tag{6}.$$

5. Derivation of final Land Surface Temperature (LST) in Celsius.

$$LST = \frac{T_B}{1 + (\frac{\lambda - T_B}{\rho})ln(\varepsilon)} - 273.15 \tag{7},$$

where λ — the wavelength of emitted radiance,
$\rho = \frac{hc}{\sigma}$ — the effective constant derived from Planck's law.

NDVI maps were generated to evaluate vegetation density and health, and were also used in the emissivity correction process. Values were classified into low, moderate, and high vegetation zones, enabling the monitoring of spatiotemporal changes in green cover across Tashkent.

District-level zonal statistics were extracted using the "Zonal Statistics as Table" tool in ArcGIS Pro. For each benchmark year, mean, maximum, and minimum values of both LST and NDVI were calculated for every district. These data supported the construction of time-series plots and comparative graphs, facilitating the analysis of vegetation decline and its correspondence with elevated surface temperatures.

Finally, correlation analysis was conducted to quantify the statistical relationship between LST and NDVI. District-level averages were compared using ArcGIS Pro's geostatistical toolbox, and Pearson correlation coefficients (R^2) were derived. Results consistently indicated a strong negative correlation, confirming the critical role of vegetation in mitigating urban heat.

All preprocessing, geospatial analysis, and visualization were conducted exclusively in ArcGIS Pro, ensuring reproducibility, spatial accuracy, and seamless integration of raster and vector datasets into a unified analytical framework.

RESEARCH RESULTS AND DISCUSSION

This study presents a multi-decadal spatial assessment of Land Surface Temperature (LST) across Tashkent, providing detailed insights into the progressive intensification of the urban heat island (UHI) effect between 2000 and 2024. Raster-based LST datasets spanning six benchmark years reveal not only substantial increases in absolute surface temperatures but also a marked expansion of spatial coverage, with significant intra-urban variability detected among the city's twelve administrative districts (Fig. 2). The results clearly demonstrate that Tashkent has undergone a consistent and intensifying UHI effect, reflecting both the scale of urban transformation and the decline of ecological buffers.

In 2000, LST values were comparatively moderate. Peripheral districts such as Yangihayot, Bektemir, and Uchtepa recorded average surface temperatures below 35 °C, largely due to lower levels of urban density and a higher prevalence of vegetation, including agricultural land and tree cover. By contrast, core districts such as Yashnabad, Mirzo Ulugbek, and Mirabad already displayed elevated LST values, indicative of early stages of urban densification and the widespread introduction of impervious materials that increase heat storage capacity.

Between 2005 and 2015, a steady rise in LST was recorded across all districts. During this decade, central and eastern districts — including Shaykhontohur, Yakkasaray, and Chilonzor — experienced notable increases of more than 2 °C, with average LSTs approaching or exceeding 36 °C. These increases correspond to phases of rapid infill construction, reduction of green cover, and replacement of natural surfaces with heat-retaining concrete and asphalt. Peripheral zones, previously moderated by agricultural buffers and open land, also began to exhibit upward thermal trends during this period, particularly in suburban areas undergoing residential and industrial expansion.

By 2020, and most prominently in 2024, thermal intensification became both spatially extensive and severe. Districts such as Mirabad, Yakkasaray, Shaykhontohur, and Yashnabad recorded average LSTs exceeding 37.5 °C, with maximum hotspot values surpassing 40 °C. The formerly cooler peripheral districts also displayed pronounced increases, highlighting a convergence of thermal regimes between urban cores and peripheral zones. This shift is directly attributable to cumulative anthropogenic modifications of the land surface, progressive vegetation loss, and heightened anthropogenic heat emissions (Fig. 3).

Analysis of NDVI patterns over the same period provides a complementary perspective on vegetation dynamics. In 2000, high NDVI values (>0.3) were concentrated in southern and northeastern districts such as Yangihayot, Bektemir, and parts of Mirzo Ulugbek, reflecting the presence of croplands, orchards, and urban green parks. Between 2005 and 2010, NDVI values declined steadily in central and eastern districts, with large zones falling below 0.2 as construction, road expansion, and industrial development intensified.

From 2015 onwards, vegetation degradation accelerated and became spatially widespread. Districts such as Sergeli, Yashnabad, and Mirabad showed particularly severe vegetation decline, with NDVI values approaching zero by 2024. The contraction of green space not only altered ecological function but also played a decisive role in the sharp increase of surface heat across the city (Fig. 4).

A statistical analysis of district-level mean values confirmed the strong inverse relationship between vegetation cover and surface temperature. A Pearson correlation coefficient ($R^2 = 0.71$) indicated that 71 % of the spatial variation in LST could be explained by differences in vegetation cover. Districts maintaining higher NDVI values consistently exhibited lower LSTs, thereby validating the established cooling effect of vegetation through shading and evapotranspiration.

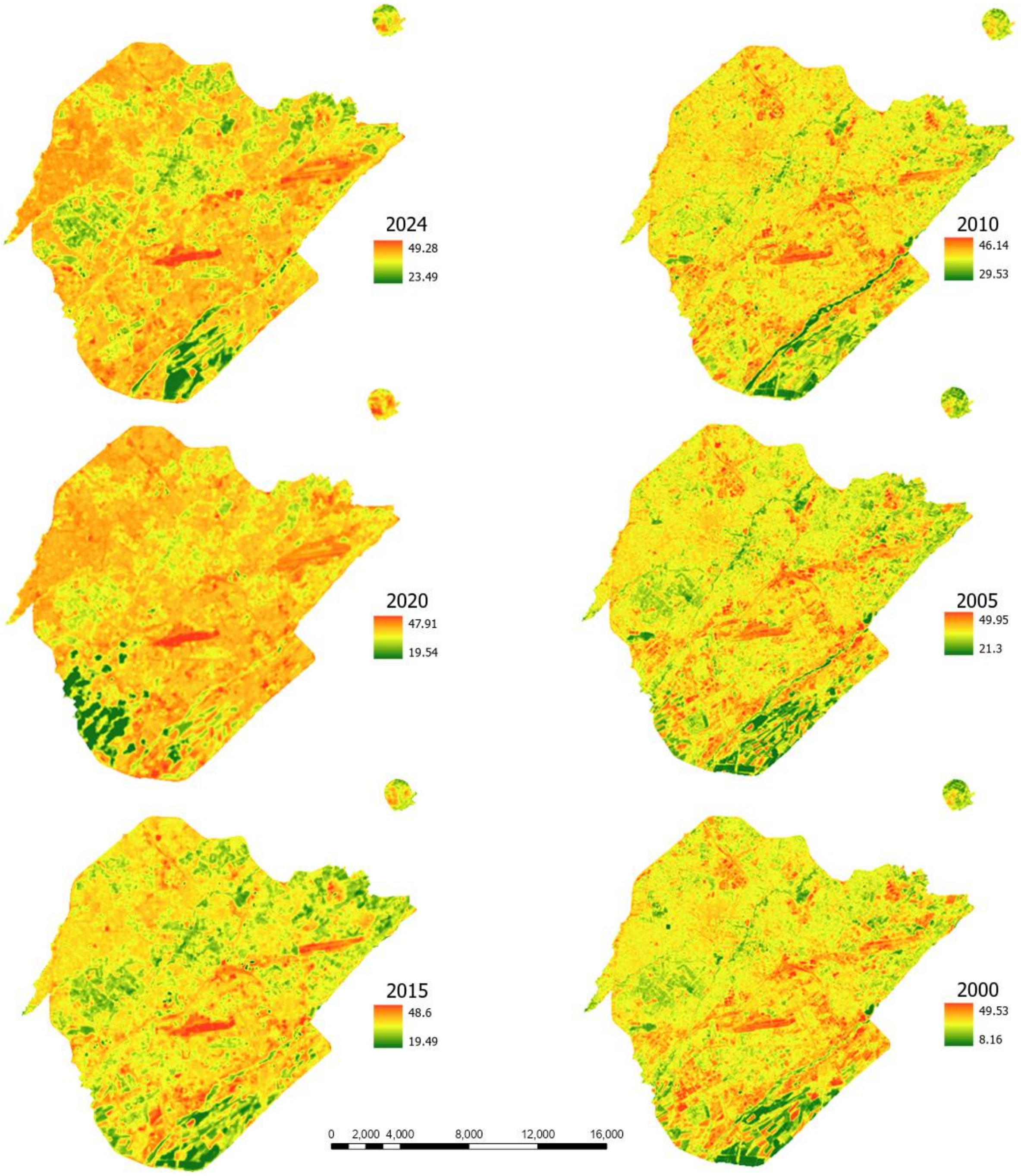

Fig. 2. Spatial distribution of Land Surface Temperature (LST) in Tashkent, 2000–2024

These results align with global research on UHI dynamics, particularly in semi-arid and arid environments where vegetation scarcity amplifies the thermal consequences of urban expansion. The observed inter-district disparities reveal a clear spatial logic: densely built-up central districts with limited vegetation have become persistent heat hotspots, while southern fringe districts with remnants of agricultural and natural vegetation have retained relatively lower LSTs, though even these areas now show upward thermal trajectories.

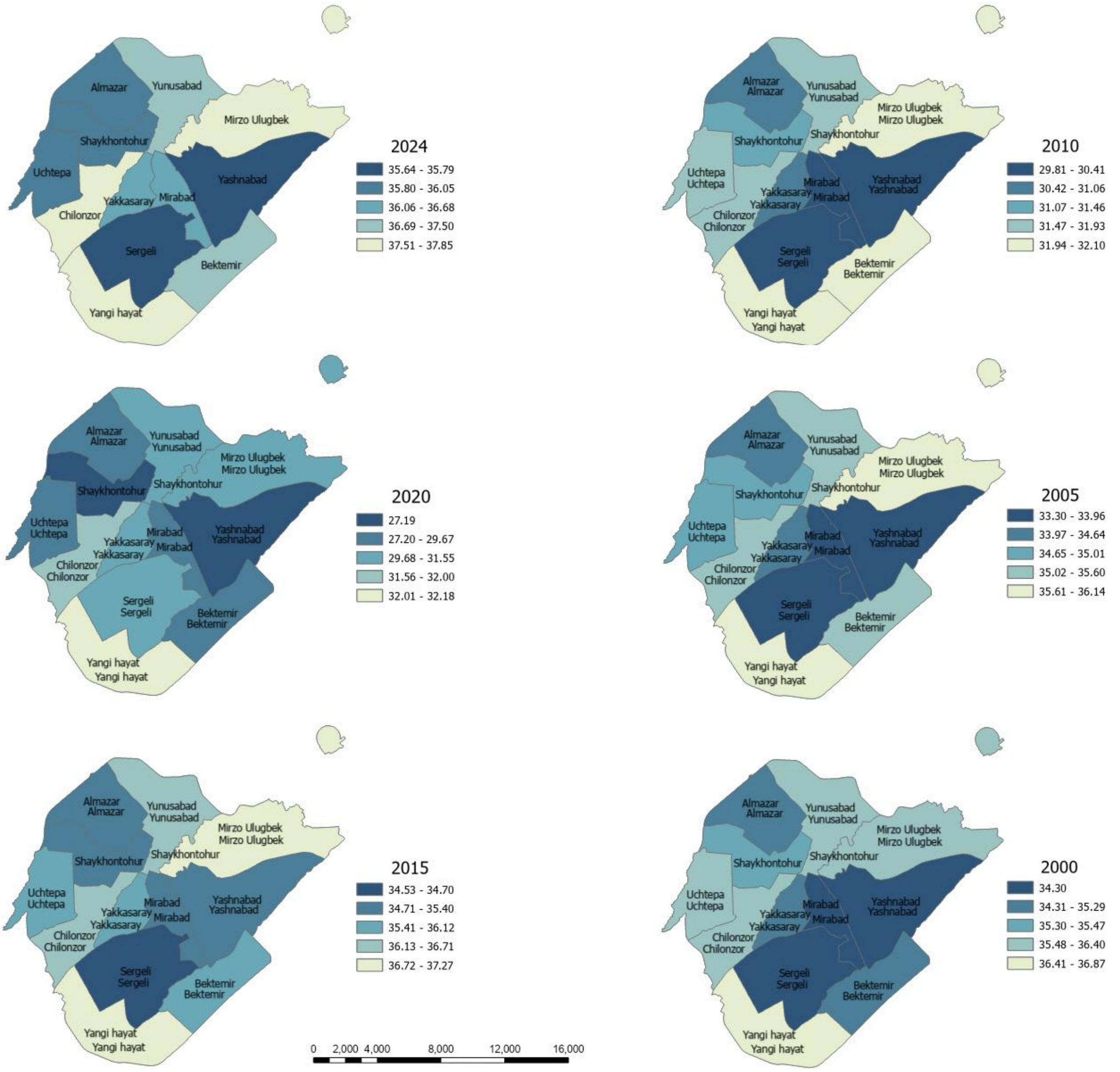

Fig. 3. Average district-level Land Surface Temperature (LST) in Tashkent, 2000–2024

The evidence presented underscores the urgent need for district-specific planning interventions. Historically, urban development in Tashkent has often occurred at the expense of ecological infrastructure, reducing the natural capacity of the city to regulate heat. Without corrective action, escalating LSTs could further exacerbate energy demand, heat-related illnesses, and long-term environmental degradation.

This study demonstrates that between 2000 and 2024, Tashkent's thermal landscape has been transformed by rapid urban growth and vegetation decline, resulting in severe heat intensification. The strong LST-NDVI correlation highlights the irreplaceable role of green infrastructure in mitigating urban heat. To address these challenges, planners and policymakers should prioritize:

- expansion and protection of urban green spaces, including public parks, green corridors, and peri-urban agricultural buffers;
- adoption of reflective and heat-reducing construction materials in building and infrastructure projects;
- integration of nature-based solutions (green roofs, vertical greening, and urban forests).

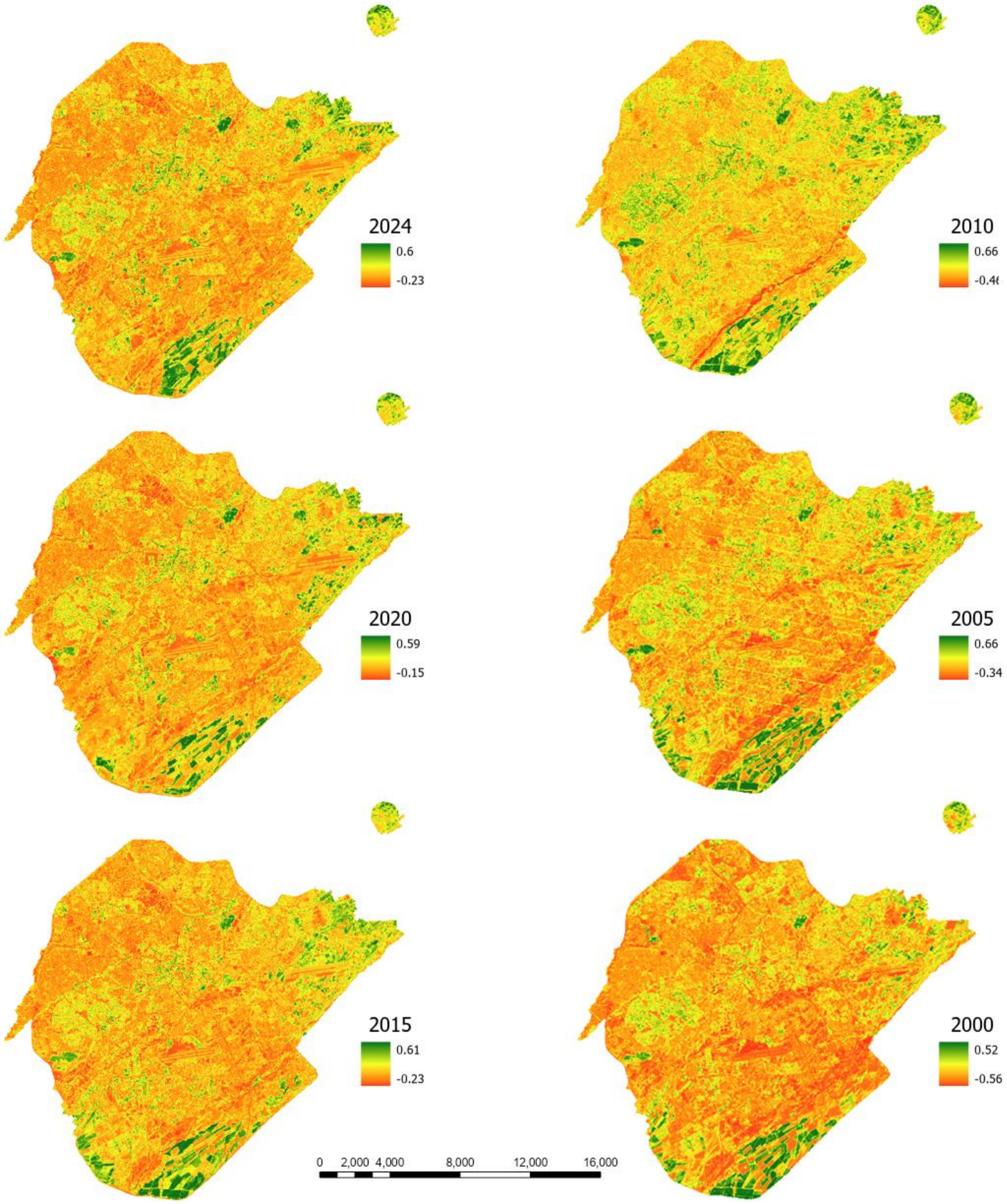

Fig. 4. Spatial distribution of the Normalized Difference Vegetation Index (NDVI) in Tashkent, 2000–2024

District-specific resilience strategies informed by spatiotemporal LST-NDVI monitoring. Regular long-term monitoring of LST and NDVI using satellite remote sensing within GIS platforms such as ArcGIS Pro is essential for adaptive and evidence-based urban planning. Such monitoring will provide the foundation for climate-resilient development pathways in Tashkent and other rapidly urbanizing cities within arid and semi-arid regions.

CONCLUSIONS

This study provides a comprehensive spatio-temporal assessment of urban heat dynamics in Tashkent over a 24-year period (2000–2024) using multi-temporal Landsat satellite imagery integrated with geospatial analysis. By combining Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) datasets, the research offers a detailed evaluation of the urban heat island (UHI) phenomenon and its ecological drivers, both at the raster pixel level and across the city's twelve administrative districts.

The results demonstrate a consistent and significant increase in surface temperatures throughout Tashkent, with particularly pronounced intensification in the central and eastern districts. Between 2000 and 2024, average LST values rose by more than 2.5 °C in several densely urbanized areas, underscoring the combined effects of accelerated land conversion, increased impervious surface coverage, and the progressive decline of vegetation. These thermal changes correspond closely with the patterns of rapid urban growth and infrastructure development observed in the city.

Simultaneously, NDVI analysis revealed a steady reduction in vegetation cover across the study period. Green areas, once concentrated in peripheral districts and peri-urban zones, became increasingly fragmented or replaced by built-up surfaces. This process diminished the capacity of the urban landscape to provide natural cooling through evapotranspiration and shading, thereby exacerbating surface heating.

A particularly important finding of this research is the strong negative correlation ($R^2 = 0.71$) between LST and NDVI, confirming that vegetation density is a decisive factor in moderating thermal environments. Districts with higher vegetation cover consistently recorded lower surface temperatures, illustrating the role of urban green infrastructure as a natural buffer against heat stress. This statistically robust relationship supports global evidence that vegetation is among the most effective, low-cost strategies for mitigating UHI impacts, especially in semi-arid continental climates such as that of Tashkent.

These insights carry direct implications for climate-adaptive urban planning. The preservation, restoration, and expansion of vegetated areas must become central to Tashkent's future development strategy. Specific measures include the creation of new urban parks, the integration of green roofs and vertical greenery into building design, and the promotion of reflective and thermally neutral construction materials. Moreover, establishing long-term monitoring frameworks based on remote sensing and GIS technologies will enable decision-makers to track thermal dynamics in real time, evaluate the effectiveness of mitigation interventions, and guide evidence-based policy.

In conclusion, the unchecked continuation of current urbanization trends in Tashkent will likely exacerbate heat-related health risks, increase energy demand, and reduce overall urban livability. Integrating thermal and ecological indicators into municipal planning frameworks is therefore essential. By embedding LST-NDVI monitoring into urban policy, Tashkent can enhance its resilience to climate change, protect public health, and ensure sustainable and climate-resilient urban development for the coming decades.

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Finally, the authors recognize the broader academic and institutional environment that enabled this study, including the availability of open-access remote sensing data from the United States Geological Survey (USGS) Earth Explorer platform and the geospatial processing capabilities of ArcGIS Pro. These resources ensured methodological robustness, reproducibility, and alignment with international best practices in geospatial and environmental research.

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