

Article

Land Cover Transformations and Thermal Responses in Representative North African Oases from 2000 to 2023

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Abstract

Oases in arid regions are critical ecosystems, providing essential ecological, agricultural, and socio-economic functions. However, urbanization and climate change increasingly threaten their sustainability. This study examines land cover (LULC) and land surface temperature (LST) dynamics in four representative North African oases: Tolga (Algeria), Nefta (Tunisia), Ghadames (Libya), and Siwa (Egypt) over the period 2000–2023, using Landsat satellite imagery. A three-step analysis was employed: calculation of NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-up Index), and LST, followed by supervised land cover classification and statistical tests to examine the relationships between the studied variables. The results reveal substantial reductions in bare soil (e.g., 48.10% in Siwa) and notable urban expansion (e.g., 136.01% in Siwa and 48.46% in Ghadames). Vegetation exhibited varied trends, with a slight decline in Tolga (0.26%) and a significant increase in Siwa (+27.17%). LST trends strongly correlated with land cover changes, demonstrating increased temperatures in urbanized areas and moderated temperatures in vegetated zones. Notably, this study highlights that traditional urban designs integrated with dense palm groves significantly mitigate thermal stress, achieving lower LST compared to modern urban expansions characterized by sparse, heat-absorbing surfaces. In contrast, areas dominated by fragmented vegetation or seasonal crops exhibited reduced cooling capacity, underscoring the critical role of vegetation type, spatial arrangement, and urban morphology in regulating oasis microclimates. Preserving palm groves, which are increasingly vulnerable to heat-driven pests, diseases and the introduction of exotic species grown for profit, together with a revival of the traditional compact urban fabric that provides shade and has been empirically confirmed by other oasis studies to moderate the microclimate more effectively than recent low-density extensions, will maintain the crucial synergy between buildings and vegetation, enhance the cooling capacity of these settlements, and safeguard their tangible and intangible cultural heritage.



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Keywords: land surface temperature (LST); land cover changes; oases; climate change adaptation; remote sensing; North Africa

1. Introduction

An oasis is a complex Saharan socio-ecological system in which water resources, mainly groundwater or flows extracted from ephemeral streams, date palm groves, and human settlements function as an integrated unit. Within this arid context, the oasis generates a distinctive microclimate that moderates regional climatic extremes and creates the conditions required for sustainable living [1–3]. This biophysical framework supports a resilient socio-economic system [2–7]. Despite their significance, oases face growing challenges due to the combined pressures of climate change and urbanization, which threaten their ecological balance and sustainability [1,2,8–10]. North Africa is predominantly characterized by arid and semi-arid climatic conditions, a trend that is intensifying due to ongoing desertification and climate change [11,12]. In this context, oases serve as critical interfaces between human and natural systems, where climatic, hydrological, and anthropogenic factors converge to shape land use, atmospheric conditions, and environmental characteristics. These ecosystems play a pivotal role in supporting environmental stability, preserving cultural heritage, and sustaining local livelihoods [8,13–15].

Over the past decades, urbanization has profoundly altered the structure and function of many oases, leading to significant changes in land use [8–10,16–18]. Built-up areas have expanded into regions traditionally covered by vegetation or bare soil, replacing natural cooling surfaces with heat-absorbing infrastructure, exacerbating the urban heat island (UHI) effect [17,19]. At the same time, climate change has intensified aridity, further straining vegetation and water resources [20–23]. These forces contribute to the increase in land surface temperature (LST), a key indicator of environmental health and human impact. The rise in LST not only worsens thermal stress and public health challenges but also disrupts agricultural productivity, threatens water resource availability in already limited regions, and increases energy consumption. This, in turn, leads to higher carbon emissions, creating a vicious cycle that further intensifies the situation [19,22,24–27].

Remote sensing has become an essential technology for studying large-scale environmental dynamics, particularly the impacts of urbanization and land use changes on environmental characteristics such as land surface temperature (LST) [28–31]. With the increasing availability of multi-temporal satellite data, researchers can analyze thermal and spatial trends over extended periods using images from satellite missions such as Landsat, MODIS, and Sentinel [32–35].

To quantify environmental and urban dynamics, several remote sensing indices have been developed to assess the interactions between land use and thermal dynamics. The Normalized Difference Vegetation Index (NDVI), which measures vegetation density and health, is commonly used to analyze changes in vegetated areas. The Normalized Difference Built-up Index (NDBI), on the other hand, identifies urban zones and their expansion, while the proportion of vegetation (Pv), derived from the NDVI, plays a central role in calculating thermal emissivity (ϵ), a crucial parameter for estimating surface temperature. Finally, LST, obtained from satellite thermal bands, provides a direct measurement of temperature variations, often linked to surface thermal properties and land use. These indices, combined with supervised classification techniques, enable a thorough analysis of land use changes and their impacts on urban and natural environments [36–39].

In recent years, numerous studies have been published analyzing the transformations of urban environments, considering not only morphological changes but also other essential characteristics such as the microclimate dynamics [40–42], the urban heat island effect [30,43–45], the vegetation health, and shifts in ecosystem services [46–49] offering a comprehensive understanding of the environmental and societal impacts of urban growth. However, this technology has been widely applied to study oases in regions like Asia (particularly in China and India) [21–24,30,37,39,50]. Despite a few notable studies conducted

in countries such as Morocco, Iraq, Egypt, and Saudi Arabia [17,20,26,51–53], research on North African and Middle Eastern oases remains limited and fragmented. This gap highlights the need for further investigation and serves as a key motivation for the present study, which aims to provide a comprehensive comparative analysis of selected representative oases in the region.

This study focuses on four North African oases: (1) Tolga (Algeria), (2) Nefta (Tunisia), (3) Ghadames (Libya), and (4) Siwa (Egypt), to evaluate changes in land use and land surface temperature (LST) over 23 years (2000–2023). These oases were selected for their environmental, agricultural, and cultural significance, as well as their representativeness of broader trends in arid and semi-arid regions. More details about the key features of the selected oases and their relevance to this study are provided in Table 1. This study aims to answer key questions: How have land use patterns evolved in these oases? What are the implications of these changes on LST? And what do these trends reveal about the broader impacts of urbanization and climate change on oasis ecosystems?

Table 1. Key features of the selected oases and their relevance to this study.

Feature	Description and Relevance to this Study
Climatic Context	All selected oases lie in arid or semi-arid regions within the Sahara Desert, offering a coherent climatic setting to assess LST and land cover dynamics under extreme conditions.
Ecological and Agricultural Importance	Each oasis is historically and ecologically significant, especially in terms of palm-based agriculture and localized biodiversity, making them critical for analyzing vegetation–temperature interactions.
Land Use Variation and Urban Pressure	These oases represent different stages of urban growth and agricultural expansion, providing the diversity necessary for assessing land cover–LST relationships using NDVI and NDBI.
Environmental Vulnerability	All oases are increasingly threatened by rising temperatures, desertification, and water scarcity, positioning them as priority zones for climate resilience analysis.
Satellite Data Availability	Consistent availability of cloud-free Landsat imagery across all sites ensures robust, standardized long-term analysis (2000–2023).
Topographic Consistency	All oases are located in relatively flat landscapes (with minimal elevation variation), reducing the impact of topography on LST measurements.

By linking land use change dynamics to land surface temperature (LST) trends, this study aligns with the findings of numerous other research efforts conducted in oases across various regions of the world, including China, India, Saudi Arabia, and the United States [8,16,17,24,50,54–56]. These converging results underscore the environmental and climatic challenges faced by oases, emphasizing the universal importance of climate-resilient urban planning strategies, vegetation restoration, and sustainable land management practices. Such measures are essential for mitigating rising temperatures and ensuring the long-term viability of these critical ecosystems.

2. Study Area

This study focuses on four major and representative oases in North Africa (Figure 1): Tolga (Algeria), Nefta (Tunisia), Ghadames (Libya), and Siwa (Egypt). These oases were selected based on their geographic, climatic, and socio-economic characteristics, ensuring both diversity and representativeness for understanding land cover and land surface temperature (LST) dynamics in arid and semi-arid regions. Table 1 summarizes the criteria used for selecting these oases, while Figure 1 illustrates their geographic locations.



Figure 1. Location of the studied oasis.

To facilitate a consistent and comparable analysis of land surface temperature (LST) dynamics and land use changes across diverse oases, circular study areas were defined for each site [51,57]. Each area was designed to encompass the urban core, surrounding vegetated zones, and adjacent bare soil, thereby capturing the key land cover types influencing thermal patterns. The diameter of each circle was adjusted to reflect the specific spatial configuration and environmental context of each oasis while also minimizing edge effects and avoiding the inclusion of nearby settlements. The selected diameters were 3.5 km for Tolga and Ghadames, 5 km for Nefta, and 7 km for Siwa. These differences account for variations in oasis morphology, urban sprawl, and land cover heterogeneity. This methodology ensures a standardized yet context-sensitive spatial framework, allowing for robust inter-site comparisons while preserving the unique ecological and thermal characteristics of each oasis [58].

3. Materials and Methods

3.1. Data Collection and Pre-Processing

This study utilized satellite imagery from Landsat 7 ETM+ (2000), Landsat 8 OLI/TIRS, and Landsat 9 OLI-2/TIRS-2 (2023) as the primary data sources [31,59]. The spatial resolution of the datasets varied by band: Reflective bands had a resolution of 30 m. In comparison, thermal bands had a resolution of 60 m for Landsat 7 and 100 m for Landsat 8/9, respectively. Thermal bands were later resampled to match the reflective bands (30 m) for consistency. Resampling is the process of adjusting the spatial resolution of a raster dataset (such as satellite imagery) to match the resolution or grid alignment of another dataset. This is especially important when combining data from multiple sources or bands that have different spatial resolutions. All images were acquired at the Level 1 Terrain Precision (L1TP) correction level, which includes both geometric and radiometric corrections, ensuring high data quality. Atmospheric corrections were also applied using ArcGIS Pro to the images to reduce atmospheric effects and ensure greater accuracy in the derived index calculations [60].

The images utilized in this study were chosen to represent the summer period, specifically the month of July, characterized by extreme summer climate conditions and minimal seasonal vegetation, which could otherwise influence NDVI calculations [53–55]. To ensure the accuracy of the analyses and reduce errors caused by cloud cover or atmospheric interference, only cloud-free scenes were included. Ten images meeting these criteria (details summarized in Table 2) were selected to enable reliable multi-temporal comparisons between the years 2000 and 2023.

Table 2. Details of remote sensing images utilized in this study.

Oasis	Year	Landsat Sensor	Spatial Resolution (m)	Bands Used	Cloud Cover (%)	Acquisition Date
Tolga (Algeria) (34.7225° N, 5.3783° E)	2000	Landsat 7 ETM+	30 (Reflective), 60 (Thermal)	Band 6 (Thermal), Band 3 (Red), Band 4 (NIR)	0.00	4 July 2000
	2023	Landsat 8 OLI/TIRS	30 (Reflective), 100 (Thermal)	Band 10 (Thermal), Band 5 (NIR), Band 4 (Red)	0.00	12 July 2023
Siwa (Egypt) (29.2032° N, 25.5196° E)	2000	Landsat 7 ETM+	30 (Reflective), 60 (Thermal)	Band 6 (Thermal), Band 3 (Red), Band 4 (NIR)	0.00	18 July 2000
	2023	Landsat 9 OLI/TIRS	30 (Reflective), 100 (Thermal)	Band 10 (Thermal), Band 5 (NIR), Band 4 (Red)	0.00	18 July 2023
Nefta (Tunisia) (33.8736° N, 7.8780° E)	2000	Landsat 7 ETM+	30 (Reflective), 60 (Thermal)	Band 6 (Thermal), Band 3 (Red), Band 4 (NIR)	0.00	22 July 2000
	2023	Landsat 9 OLI/TIRS	30 (Reflective), 100 (Thermal)	Band 10 (Thermal), Band 5 (NIR), Band 4 (Red)	0.00	2023 July 22
Ghadames (Libya) (30.1333° N, 9.5000° E)	2000	Landsat 7 ETM+	30 (Reflective), 60 (Thermal)	Band 6 (Thermal), Band 3 (Red), Band 4 (NIR)	0.00	15 July 2000
	2023	Landsat 8 OLI/TIRS	30 (Reflective), 100 (Thermal)	Band 10 (Thermal), Band 5 (NIR), Band 4 (Red)	0.00	16 July 2023

3.2. Variable Calculations

The methodology employed in this study consisted of three main steps: NDVI and NDBI calculation, estimation of land surface temperature (LST), and land cover classification. Each step was carried out using ArcGIS Pro, which provided a robust and integrated platform for data processing, analysis, and visualization. This approach ensured reliable and accurate results for analyzing vegetation density, surface temperature dynamics, and land cover changes across the selected oases. Table 3 summarizes the key processes, formulas, and tools used in the analysis [37,53,61–65].

Table 3. Key methodological steps, formulas, and tools used.

Step	Description	Formula/Details
1. Radiance Calculation	DN values from the thermal band were converted to radiance using metadata parameters.	$L\lambda = ML \cdot Q_{cal} + AL$ [39] ML: Radiance Mult Band, AL: Radiance Add Band, Qcal: DN values.
2. (BT)	Radiance was converted to brightness temperature (Kelvin).	$BT = K_2 / \ln((K_1 / L\lambda) + 1)$ [39] K_1, K_2 : Thermal constants (from metadata)
3. Proportion of Vegetation (Pv)	Proportion of vegetation was derived from NDVI.	$Pv = ((NDVI - NDVI_{min}) / (NDVI_{max} - NDVI_{min}))^2$ [66]
4. Emissivity (ε)	Emissivity was computed based on Pv to account for surface properties.	Landsat 7: $Ev = 0.004 \cdot Pv + 0.986$ Landsat 8, 9: $Ev = 0.00149 \cdot Pv + 0.98481$ (updated equation) [67]

Table 3. *Cont.*

Step	Description	Formula/Details
5. LST Calculation	LST was calculated from BT and emissivity.	$LST = BT / (1 + (\lambda BT / \rho) \ln(\epsilon))$ [61,63] λ : Thermal band wavelength, $\rho = 1.438 \cdot 10^{-2}$
6. NDVI Calculation	NDVI was computed to assess vegetation density using the Red and NIR bands.	$NDVI = (NIR - Red) / (NIR + Red)$ [66] Landsat 7: NIR (Band 4), Red (Band 3); Landsat 8/9: NIR (Band 5), Red (Band 4).
7. NDBI Calculation	NDBI was computed to identify built-up areas using the SWIR and NIR bands.	$NDBI = (SWIR - NIR) / (SWIR + NIR)$ [38] Landsat 7: SWIR (Band 5), NIR (Band 4); Landsat 8/9: SWIR (Band 6), NIR (Band 5).
8. Land Cover Classification	Supervised classification (Maximum Likelihood) [68] was employed to classify land cover types: urban, vegetation, and bare soil.	

3.3. Land Cover Classification

Land cover classification was performed using a supervised classification approach using ArcGIS Pro [52,62,68]. The classification focused on three primary land cover types: urban, vegetation, and bare soil [51,69] (Table 4).

Table 4. Land cover classes and corresponding land use types.

Class	Description
Built-up (Urban)	Residential areas, settlements, industrial zones, commercial areas, and roads.
Bare Land (Bare Soil)	Open spaces, barren soil, abandoned lands, and uncultivated areas.
Vegetation	Palm groves, crop fields, cultivated lands, fruit orchards, gardens, vegetative areas.

To evaluate the accuracy of the land cover classification, which was used to calculate the area and rate of change for the three classes between 2000 and 2023, 50 random points per class were validated using Google Earth imagery [62,70]. The Accuracy Assessment tool in ArcGIS Pro was employed to calculate the overall accuracy and Cohen's kappa coefficient (Table 5) [52,71,72].

Table 5. Classification accuracies of land cover maps.

Oasis	2000	2023	2000	2023
	Overall Accuracy (%)		Kappa Coefficient	
Tolga	0.91	0.94	0.86	0.90
Nefta	0.95	0.95	0.91	0.92
Ghadames	0.93	0.95	0.85	0.90
Siwa	0.95	0.91	0.93	0.87

3.4. Statistical Analysis

Correlation and regression analyses were conducted using IBM SPSS Statistics, version 15.0, to explore the relationships between land surface temperature (LST), the Normalized Difference Vegetation Index (NDVI), and the Normalized Difference Built-up Index (NDBI) for each oasis and year. For the correlation analysis, Pearson correlation coefficients were calculated to determine the strength and direction of the relationships between LST, NDVI, and NDBI. In the multiple linear regression analysis, LST was designated as the dependent variable, while NDVI and NDBI were treated as independent variables. The regression

model's performance was assessed using the coefficient of determination (R^2) to evaluate the model's fit [73].

4. Results

4.1. Land Cover Classification Accuracy Assessment

The accuracy of the land cover classification was assessed using Overall Accuracy (OA) and Cohen's Kappa Coefficient (Table 5). Overall Accuracy ranged from 91.00% to 95.00% in 2000 and 2023 (OA above 85.00%). Similarly, Cohen's Kappa Coefficient values ranged from 0.85 to 0.93 in 2000 and 0.87 to 0.92 in 2023 (Kappa above 0.70), reflecting strong agreement between the classified maps and the reference data [51,74–76], with minor variations observed across the oases due to the complexity of land cover variation.

4.2. Temporal and Spatial Analysis of LST and Land Cover

4.2.1. Area Change Analysis

Figures 2 and 3 illustrate the area changes and the rate of change observed in the three studied classes across the four oases between 2000 and 2023.

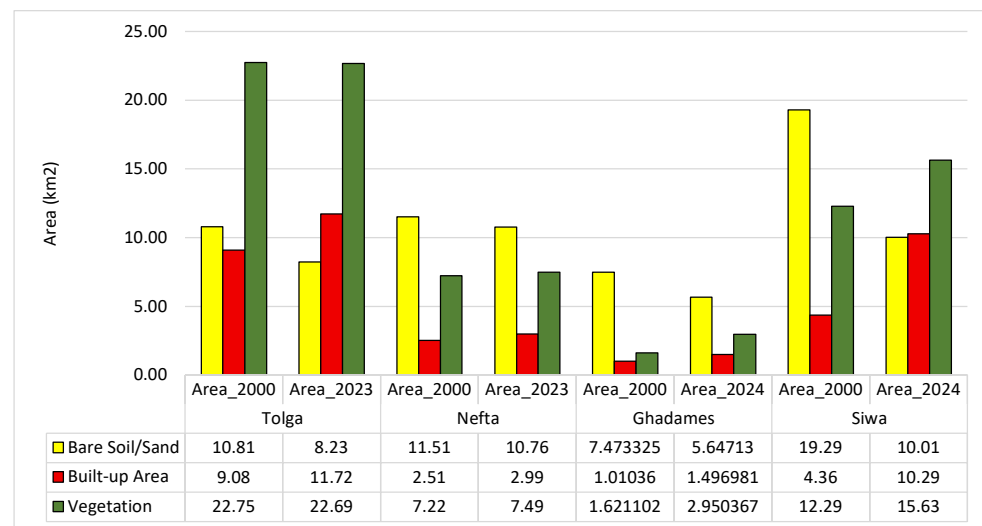


Figure 2. Land cover changes in area between 2000 and 2023.

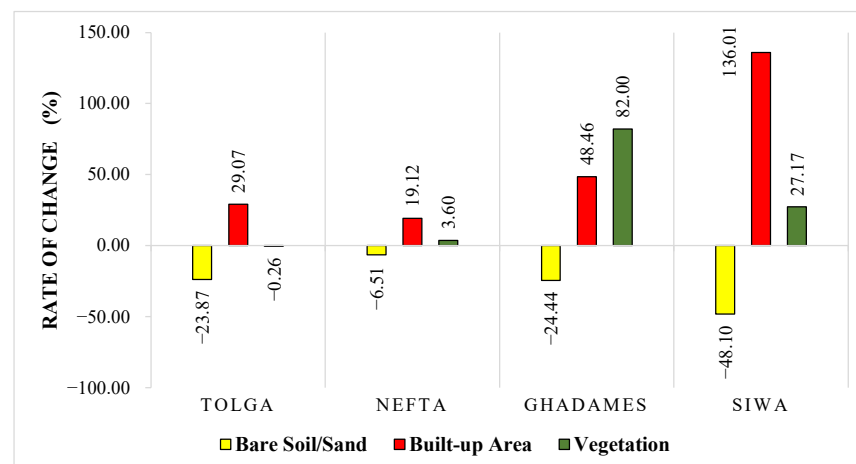


Figure 3. Rate of change (%) in land cover classes across the four oases between 2000 and 2023.

(a) Transformation of bare soil areas

The results highlight a significant reduction in bare soil across all four oases, reflecting a consistent trend of land conversion to urban or vegetative uses. Siwa showed the most substantial decrease, with a loss of 48.10%, driven by extensive urban development and agricultural expansion in response to increasing economic and demographic pressures. Tolga and Ghadames also experienced considerable reductions of 23.87% and 24.44%, respectively. These changes reflect the conversion of barren land into more productive areas, particularly for urbanization and agriculture. In contrast, Nefta experienced a more modest reduction of 6.51%, indicating a slower rate of land transformation, likely due to relatively stable socio-economic conditions.

(b) Transformation of built-up areas

Siwa recorded the most substantial expansion in built-up areas, with a 136.01% increase over the study period. This rapid growth corresponds with a demographic increase of over 60.60% between 2000 and 2015, which represents the period for which data is available for all oases [77], reflecting intense pressure on land for housing and infrastructure. Ghadames experienced a notable 48.46% increase in urban land cover, despite a more moderate population growth of 27.40% between 2000 and 2015 [77]. This expansion may be explained by the prevailing urbanization model, characterized by a low-density urban fabric that contrasts sharply with the compact, traditional settlement patterns.

Tolga, on the other hand, exhibited a 29.07% increase in built-up areas, which is relatively modest considering its higher population growth rate of 43.50% between 2000 and 2015 [77]. This contrast may reflect spatial constraints imposed by the dominance of highly productive agricultural land, particularly the economically valuable date palm groves, which have persisted over time and act as a barrier to urban sprawl. Alternatively, the slower urban expansion could indicate more deliberate and controlled urban planning, shaped by the local knowledge and practices of residents and the regulatory oversight of local authorities.

Nefta showed the most modest growth in urban areas, with a 19.12% increase, which is consistent with its relatively low population growth of 8.60% between 2000 and 2015 [77]. This pattern likely reflects a stable socio-economic context and limited external development pressures.

(c) Transformation of vegetation areas

Vegetation changes varied across the oases, reflecting differences in land management practices and environmental conditions. Ghadames and Siwa exhibited the most significant gains in vegetative cover, with increases of 82.00% and 27.17%, respectively. These increases suggest an intensification of agricultural activity, potentially supported by the development of irrigation systems and the reclamation of previously unused land. Nefta experienced a slight increase of 3.60%, indicating stable agricultural practices. Conversely, Tolga recorded a modest decline of 0.26%, which may reflect the steady nature of its agricultural system. However, this slight reduction also highlights the encroachment of urban areas on palm groves, likely due to the scarcity of vacant land and the legal protection of agricultural zones under Algerian land use policy [78].

4.2.2. Land Surface Temperature (LST) Variations

The analysis of land surface temperature (LST) variations between 2000 and 2023, based on the data presented in Figure 4, reveals significant changes across the studied oases, reflecting the impact of land use changes.

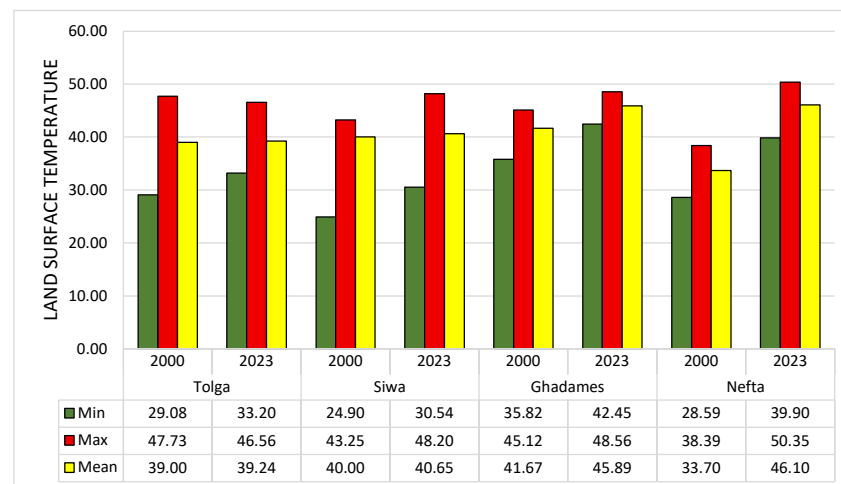


Figure 4. Temporal dynamics of land surface temperature (LST) in the studied oases (2000–2023).

Minimum temperatures increased across all oases, highlighting a general warming trend. In Tolga, they rose from 29.00 °C in 2000 to 33.00 °C in 2023. Ghadames experienced a particularly pronounced increase, with minimum temperatures rising from 35.82 °C to 42.45 °C, reflecting the growing pressures on these vulnerable ecosystems. Nefta and Siwa also recorded significant increases, rising from 28.59 °C to 39.9 °C and from 24.90 °C to 30.54 °C, respectively.

Maximum temperatures exhibited distinct trends across the oases. In Tolga, they remained relatively stable, decreasing slightly from 47.00 °C in 2000 to 46.00 °C in 2023. Conversely, moderate increases were observed in Ghadames and Siwa, with maximum temperatures reaching 48.56 °C and 48.20 °C, respectively, in 2023. Nefta, however, showed the most significant rise, with maximum temperatures climbing from 38.39 °C to 50.35 °C, indicating accelerated warming in this region. Finally, average temperatures revealed varied dynamics. In Tolga and Siwa, they remained relatively stable, around 39.00 °C in Tolga and increasing modestly from 40.00 °C to 40.65 °C in Siwa, suggesting a certain degree of thermal resilience. In contrast, Ghadames showed a notable increase, from 41.67 °C to 45.89 °C. Nefta recorded the most pronounced change, with average temperatures rising sharply from 33.70 °C in 2000 to 46.10 °C in 2023.

4.3. Analysis of Land Cover and LST Relationship Through Maps (2000–2023)

The analysis of the LC and LST maps of the four oases for the years 2000 and 2023 (Figure 5) reveals a significant relationship between the distribution of surface temperatures (LST) and land cover (LC). The lowest temperatures are consistently associated with vegetated areas, represented as green patches on the LST maps. This cooling effect is attributed to evapotranspiration and the vegetation's ability to absorb heat. In contrast, bare soil areas exhibit higher temperatures, often exceeding those of urban areas. This observation is explained by the thermal properties of bare soil, which, in the absence of vegetation or shade, accumulates and releases heat more efficiently than built surfaces. Urban areas generally show higher temperatures than vegetated zones but are slightly cooler than bare soil in some cases. This may be due to the shading effect created by urban structures or the dissipation of heat within these areas. The evolution between the two dates shows varied dynamics depending on the oasis, with urban expansion observed in some cases. However, there is no generalized decrease in vegetative cover. These variations highlight the importance of considering local specificities when analyzing the impacts of urban development and land use changes on the microclimate of each oasis. Notably, the temperature in the historical cores of the oases, where the urbanization system is traditional

and integrated with the palm groves, is lower than in the new extensions that adopt an imported urbanization model, foreign to these oases. These new extensions, with generally lower built density, contrast with the traditionally dense construction of local systems. This contrast results in an increase in exposed open spaces subject to solar radiation, contributing to a significant rise in land surface temperature (LST).

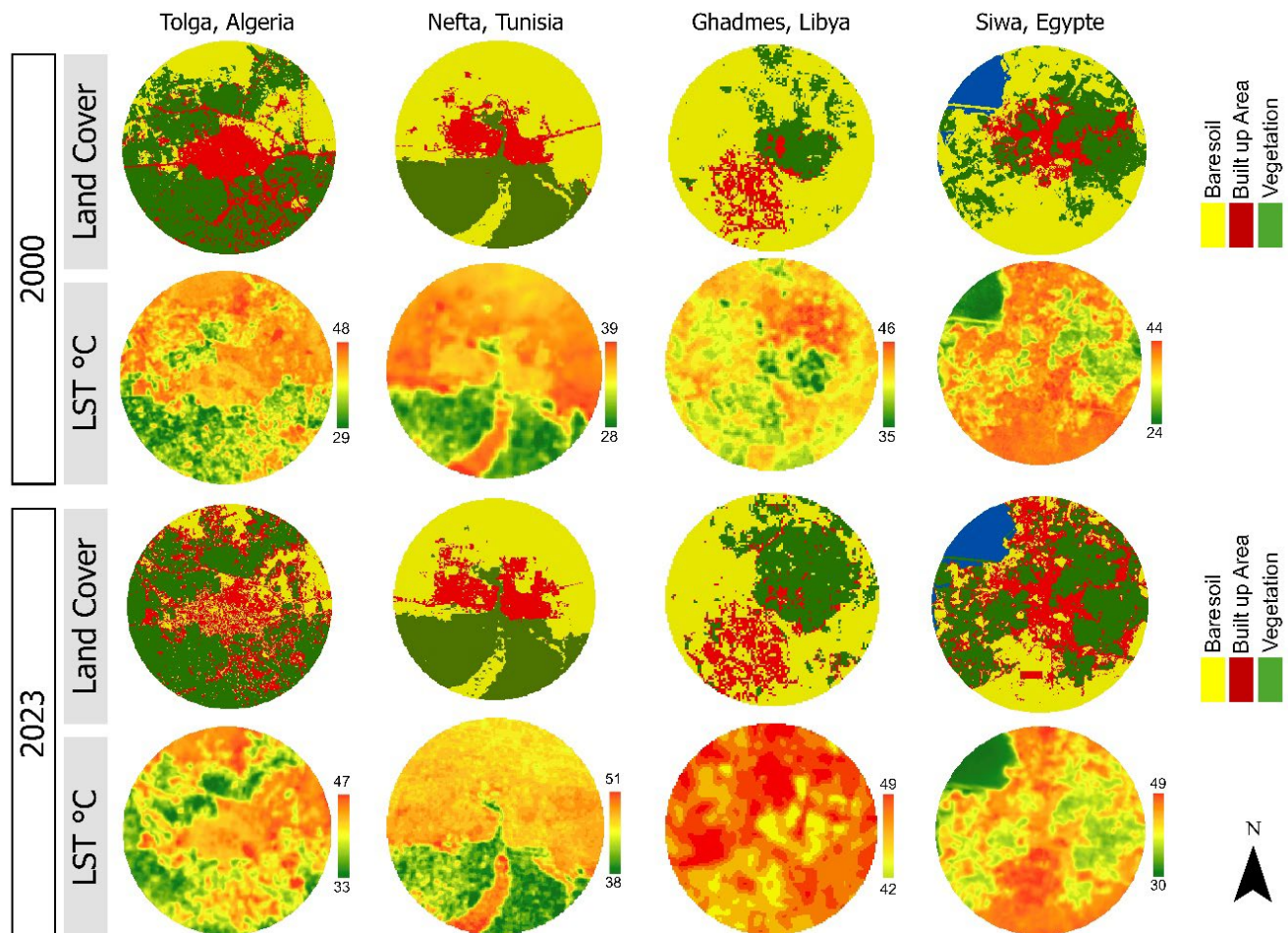


Figure 5. Land cover and land surface temperature (LST) maps of the four oases for 2000 and 2023.

4.4. Analysis of LST, NDVI, and NDBI Relationships Through Statistical Tests

4.4.1. Pearson Correlation Analysis Between LST, NDVI, and NDBI

Pearson correlation analysis was used to examine the strength and direction of potential linear relationships between LST, NDVI, and NDBI. Correlation coefficients (r) were calculated for each oasis and the two study years (2000 and 2023). This approach allowed for the identification of both global trends and site-specific patterns. The results are presented in Table 6, providing a detailed overview of the correlation values for each oasis and period.

The Pearson correlation analysis reveals differentiated dynamics between land surface temperature (LST), vegetation (NDVI), and built-up areas (NDBI) across the four studied oases. Strong negative correlations between LST and NDVI confirm the cooling effect of vegetation. In contrast, positive correlations between LST and NDBI highlight the contribution of built-up areas to surface temperature increases. However, these relationships vary among the oases, reflecting local specificities in urbanization, vegetation cover, and land management practices.

Table 6. Correlation analysis between LST, NDVI, and NDBI for selected oases (2000 and 2023).

Oasis	Year	LST-NDVI Correlation (r)	Sig. (2-tailed)	LST-NDBI Correlation (r)	Sig. (2-tailed)
Tolga	2000	−0.931 **	0.000	0.850 **	0.000
	2023	−0.838 **	0.000	0.858 **	0.000
Ghadames	2000	−0.385 **	0.000	0.409 **	0.000
	2023	−0.132 **	0.000	0.193 **	0.000
Nefta	2000	−0.896 **	0.000	0.911 **	0.000
	2023	−0.900 **	0.000	0.915 **	0.000
Siwa	2000	−0.359 **	0.000	0.348 **	0.000
	2023	−0.290 **	0.000	0.288 **	0.000

** Correlation is significant at the 0.01 level (2-tailed).

In oases such as Tolga and Nefta, the results show strong negative correlations between LST and NDVI, indicating a clear association between increased vegetation cover and lower surface temperatures. Simultaneously, high positive correlations between LST and NDBI suggest that urban expansion plays a significant role in surface warming, underscoring the urban heat island effect in these more anthropogenically altered environments. Conversely, in Ghadames and Siwa, the correlations are more moderate. In Ghadames, this reflects limited urbanization and sparse vegetation, which reduces the influence of human-induced transformations on surface temperatures. In Siwa, the relationships appear more stable over time, likely due to a relatively balanced coexistence between agricultural practices and the gradual growth of built-up areas.

4.4.2. Multiple Linear Regression Analysis

Multiple linear regression was used to evaluate the effect of NDVI and NDBI on land surface temperature (LST), defined as the dependent variable, with NDVI and NDBI as independent predictors. This method quantified the relative contribution of each index to temperature variations and identified potential interactions between these variables, highlighting the combined impacts of environmental and anthropogenic dynamics in the studied oases. The results are summarized in Table 7.

Table 7. Results of multiple linear regression analysis for LST, NDVI, and NDBI.

Oasis	Year	R	R ²	Adjusted R ²	F-Value	Sig	NDVI Coefficient (B)	NDVI Sig	NDBI Coefficient (B)	NDBI Sig
Tolga	2023	0.86	0.74	0.74	2861.34	0.00	−7.67	0.00	15.34	0.00
	2000	0.93	0.87	0.87	6514.50	0.00	−23.32	0.00	2.06	0.00
Ghadames	2023	0.21	0.04	0.04	40.76	0.00	5.02	0.00	0.83	0.23
	2000	0.44	0.19	0.19	211.08	0.00	−4.37	0.00	7.92	0.00
Nefta	2023	0.92	0.84	0.84	5085.92	0.00	2.16	0.08	21.06	0.00
	2000	0.91	0.83	0.83	4839.49	0.00	2.57	0.00	14.80	0.00
Siwa	2023	0.85	0.72	0.72	2517.63	0.00	20.66	0.00	43.04	0.00
	2000	0.36	0.13	0.13	144.49	0.00	−1.58	0.00	−11.16	0.00

The coefficient of determination indicates a strong fit for Tolga ($R^2 = 0.87$ in 2000 and 0.74 in 2023) and Nefta (0.83 in 2000 and 0.84 in 2023). At Siwa, the model still performs well in 2023 ($R^2 = 0.72$) but poorly in 2000 (0.13). In contrast, Ghadames shows an adjusted

R^2 of only 0.04 in 2023, which implies that factors not captured by NDVI and NDBI, such as vegetation quality, irrigation practice, soil reflectance, or building morphology, dominate surface-temperature variability that year.

NDVI is usually negatively correlated with LST, confirming the cooling role of vegetation, as illustrated by Tolga 2000 where NDVI equals -23.316 $p < 0.001$. However, three cases diverge from this pattern. At Nefta 2023, the NDVI coefficient is small and not statistically significant, $B = 2.156$, $p = 0.075$; such a weak signal may reflect limited NDVI variance, pixel mixing of irrigated plots and bare soil. Higher-resolution imagery, for example, drone data, together with in situ measurements of surface temperature, soil moisture, and leaf density, will be needed to clarify the relationship. In Ghadames 2023, NDVI appears positive, $B = 5.02$, $p < 0.001$, yet the model explains almost none of the variance, adjusted $R^2 = 0.04$, collinearity with NDBI is high, and $VIF > 8$; ridge regression lowers the slope to about 1.3 °C, $p \approx 0.04$, indicating that the initial value is mostly a statistical artefact. Detailed landscape segmentation and ground-based radiative measurements will be required to isolate the true effect of the residual vegetation. Finally, Siwa 2023 shows a strongly positive NDVI coefficient, $B = 20.66$, $p < 0.001$, a pattern consistent with intensively irrigated yet unshaded vegetable fields where wet soil heats rapidly despite high greenness; simultaneous records of air temperature, humidity, and surface albedo will help quantify this behavior.

The variations observed between 2000 and 2023 reveal specific temporal dynamics in the studied oases. In Tolga, the relationship between NDVI and LST appears to have stabilized, while the influence of NDBI on surface temperatures has become more pronounced. Contrary to the common assumption that vegetation inevitably declines with urbanization, the results suggest that vegetative cover has remained relatively stable in certain oases. However, this stability has not been sufficient to counterbalance the significant expansion of built-up areas. The resulting imbalance has weakened the natural thermal regulation of these environments and disrupted the ecological equilibrium of oasis ecosystems.

5. Discussion

Urbanization and changes in vegetation cover significantly influence variations in land surface temperature (LST) within oases. The strong negative correlations between LST and NDVI, particularly observed in Tolga, where dense palm groves dominate the landscape [79,80], and in Nefta, characterized by dense palms associated with agricultural crops [81], highlight the cooling effect of traditional palm groves (Figure 6). In contrast, in oases such as Ghadames, where isolated palms coexist with scattered agricultural plots [82], and Siwa, which combines palms, olive trees, and vegetable crops [83], mixed vegetation and sparse seasonal crops, characterized by their low height and limited shading, predominate. These oases exhibit a weaker correlation between LST and NDVI, indicating a relatively limited ability of the vegetation to mitigate surface temperature increases.

This difference can be attributed to the ability of palm groves, adapted to arid conditions, to provide permanent shade, maintain relative humidity, and reduce solar absorption, even during the extreme heat of summer, unlike the superficial crops found in Ghadames. These findings underscore the vital importance of preserving traditional palm grove systems, which serve as crucial thermal regulators for oases. However, the gradual replacement of these groves by urbanized areas or seasonal crops, often considered more profitable, risks exacerbating the urban heat island effect and compromising the sustainability of oases in the face of increasing challenges posed by urbanization and climate change. It is also important to note that the palm groves themselves are under threat from climate change and rising temperatures, which, according to several studies, promote the spread of diseases affecting date palms and degrade the quality of dates [84–88]. This situation

makes date farming increasingly unprofitable, driving many farmers to turn to other types of vegetation, which could further disrupt the ecological and thermal balance of oases.

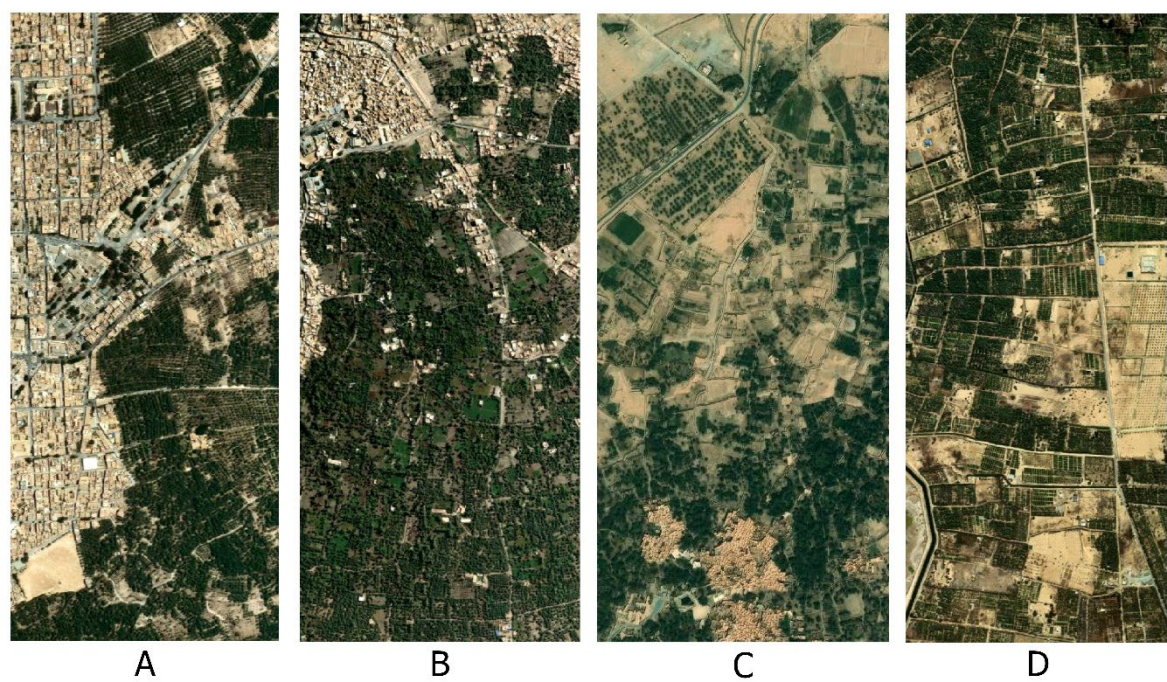


Figure 6. Zoom on representative vegetation patterns in the four oases. (A): Tolga (dense palm); (B): Nefta (dense palms and agricultural crops); (C): Ghadames (isolated palms with scattered agricultural plots); and (D): Siwa (palms combined with olives and vegetable crops).

Urbanization patterns in oases also shape their microclimate. Two contrasting fabrics stand out. The traditional fabric in the historic core is compact, built with locally adapted materials, and merges seamlessly with surrounding palm groves. This configuration creates shade and encourages natural ventilation. Measured daytime LST averages confirm the cooling benefit: In Tolga, Nefta, and Ghadames, the historic quarters record mean values of 38.8, 45.1, and 43.6 °C, respectively, while the adjacent modern extensions reach 41.3, 47.1, and 45.3 °C. The resulting thermal gaps are 2.5 °C in Tolga, 2.1 °C in Nefta, and 1.7 °C in Ghadames (Table 8; Figure 7).

Table 8. Comparative summary of demographic change, land cover dynamics, vegetation patterns, and thermal trends in four North African oases (2000 to 2023).

Criterion (2000–2023)	Tolga	Nefta	Ghadames	Siwa
Population change (%)	+43.50	+8.60	+27.40	+60.60
Built-up area change (%)	+29.07	+19.12	+48.46	+136.01
Vegetation cover change (%)	−0.26	+3.6	+82.00	+27.17
Bare-soil change (%)	−23.87	−6.51	−24.44	−48.10
Mean LST rise (°C)	+0.24	+12.4	+4.22	+0.65
Representative Vegetation Patterns	Dense palm	Dense palms and agricultural crops	Isolated palms with scattered agricultural plots	Palms combined with olives and vegetable crops

LST measures the skin temperature of roofs and exposed ground surfaces, not the air temperature experienced by pedestrians, although the two are closely related. Narrow shaded streets, arcades, and covered passages that characterize many historic cores in the

oasis can remain several degrees cooler than the roof surfaces detected by satellite sensors. The actual microclimate gap between traditional and modern quarters is therefore likely larger than the surface temperature difference reported here

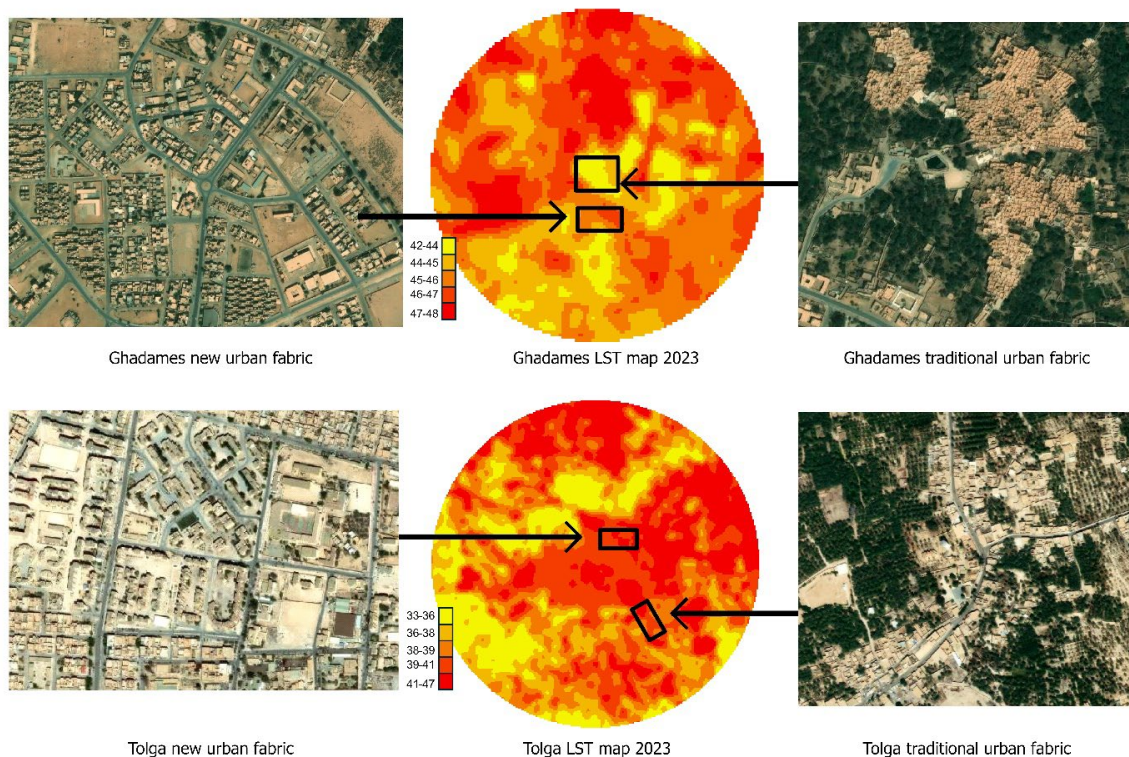


Figure 7. Comparison of traditional and new urban fabrics in relation to LST distribution (2023).

Modern extensions, often designed to external planning standards, are laid out at low density with large open spaces fully exposed to solar radiation. They also break the physical and functional link between the built environment and the palm groves. This lack of integration explains the higher surface temperatures in the newer quarters (Table 9). This study does not report a traditional versus modern LST contrast for Siwa because its urban fabric is distinctive. Much of the settlement has been rebuilt in a uniform architectural style, and the recent extensions largely replicate the existing street network. Consequently, the physical characteristics are too similar for the current indicators to identify two morphologically distinct zones, making a comparative analysis uninformative. Detecting any microclimatic gradient within Siwa would require a dedicated ground-based survey, which is proposed as an objective for future research.

Table 9. LST 2023 comparison of traditional vs. modern urban fabric.

Oasis	LST Moyenne Tissu Traditionnel (°C)			LST Moyenne Extension Moderne (°C)			Δ LST (°C)
	Min	Max	moyenne	Min	Max	moyenne	
Tolga	33.63	43.27	38.80	36.28	46.55	41.30	2.5
Nefta	42.06	47.85	45.07	46.60	49.61	47.12	2.05
Ghadames	42.21	45.69	43.55	43.66	47.02	45.25	1.7
Siwa	/	/	/	/	/	/	/

These findings highlight the critical importance of preserving and integrating traditional urban planning practices, which are particularly well-suited to arid climatic conditions, into the urban management strategies of oases; neglecting these lessons risks

undermining the sustainability of oases while amplifying the negative effects of climate change and urban heat islands.

Limitations and Future Implications

This study provides valuable insights into the relationship between land cover transformations and land surface temperature dynamics in North African oases, a region that remains relatively underexplored in the literature. It offers a robust and replicable methodological framework, previously applied to oases in other continents. However, several limitations should be acknowledged. This study relies exclusively on remote sensing data, without complementary in situ validation of land surface temperature or vegetation condition, which may affect the accuracy of the interpretations. The use of a circular study area, although methodologically consistent, may not fully reflect the spatial complexity of irregular urban and agricultural forms. Additionally, the land cover classification was limited to three broad categories, which may obscure more specific land use types such as water bodies, seasonal vegetation, or degraded zones. The analysis was based solely on summer imagery, particularly from July, which restricts the exploration of seasonal variations in microclimatic behavior. Moreover, the absence of socio-economic variables, including population growth, land management practices, and policy frameworks, due to a lack of available data, limits the ability to assess the full scope of drivers behind oasis transformation.

Another key limitation of the present work is the lack of very high-resolution imagery needed to quantify greenery within the built environment of the four case studies. Features such as narrow palm grove strips, courtyard gardens, and street trees fall below the thirty-meter Landsat pixel size. This constraint applies only to intra urban vegetation estimation and does not affect the accuracy of our other land cover metrics. Future research should combine sub meter multispectral data acquired by drones or PlanetScope satellites with field-based canopy surveys. Such a workflow would allow calculation of an urban green space ratio for each oasis, facilitate completion of vegetation thresholds derived from remote sensing, and support scenario testing of blue and green infrastructure designed to mitigate thermal stress.

To overcome these limitations, future research should incorporate in situ observations, multi-seasonal and diurnal satellite data, and higher-resolution imagery to enhance both spatial and temporal accuracy. Expanding the land cover classification to include more detailed categories would improve the granularity of analysis. Comparative studies across a broader range of North African oases are also recommended to inform the development of context-sensitive strategies for sustainable land use and climate-resilient urban planning in arid regions.

6. Conclusion

This study highlights the complex interactions between land surface temperature (LST), vegetation cover, and urbanization in arid oases, emphasizing the environmental impacts of anthropogenic activities. The findings demonstrate the significant cooling effect of traditional palm groves, the warming influence of built-up areas, and the critical role of urbanization and urban morphology in shaping these dynamics. The variability of these relationships across regions and study periods reflects the diverse challenges faced by oases.

The temporal analysis reveals an increasing influence of urbanization on LST, as evidenced by the high NDBI coefficients between 2000 and 2023 in most cases. While Tolga appears to have maintained a certain thermal balance through a relatively stable relationship between urban expansion and vegetation, other oases such as Ghadames

and Siwa face more complex challenges. These challenges suggest the need to consider additional factors beyond NDVI and NDBI to understand their thermal dynamics fully.

In response to the growing challenges posed by rising temperatures and urban heat islands, this study proposes sustainable management strategies tailored to the specific needs of oases. These strategies include preserving and strengthening traditional palm groves, which serve as vital thermal regulators, creating urban green spaces designed to address the climatic constraints of arid regions, and promoting a dense urbanization model harmonized with the environment. These measures are essential to mitigating thermal impacts, preserving ecological balance, and ensuring the long-term resilience of oases in the face of urbanization and climate change.

To deepen this understanding, future research should integrate complementary variables such as microclimatic characteristics and the type and health of vegetation cover. Remote sensing analyses would also benefit from being complemented by in situ studies. Furthermore, comparative studies conducted across different arid regions could refine management approaches, providing practical and targeted recommendations for policymakers and stakeholders involved in the sustainable development of oases.

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

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