

THERMAL CHARACTERIZATION OF THE UNIVERSITY ENVIRONMENT FOR GREEN INFRASTRUCTURE PLANNING

Recibido 07/03/2026
Aceptado 24/04/2026

CARACTERIZACIÓN TÉRMICA DEL ENTORNO UNIVERSITARIO PARA LA PLANIFICACIÓN DE INFRAESTRUCTURA VERDE

CARACTERIZAÇÃO TÉRMICA DO AMBIENTE UNIVERSITÁRIO PARA O PLANEJAMENTO DE INFRAESTRUTURA VERDE

Walter Ávila-Ruiz

Magíster en Ingeniería
Estudiante de Doctorado de la Facultad de Ingeniería
Universidad Autónoma de Baja California
Mexicali, México
<https://orcid.org/0009-0000-3450-1194>
walter.avila@uabc.edu.mx

Carlos Salazar-Briones (autor correspondencia)

Doctor en Ciencias
Profesor investigador de la Facultad de Ingeniería
Universidad Autónoma de Baja California
Mexicali, México
<https://orcid.org/0000-0002-5237-5539>
csalazar86@uabc.edu.mx

José Ruiz-Gibert

Doctor en Ciencias
Profesor investigador de la Facultad de Ingeniería
Universidad Autónoma de Baja California
Mexicali, México
<https://orcid.org/0000-0003-4532-7413>
mizael.ruiz@uabc.edu.mx

Juan Saiz-Rodríguez

Doctor en Ciencias
Profesor investigador del Departamento de Ingeniería Civil y Minas
Universidad de Sonora
Hermosillo, México
<https://orcid.org/0000-0002-0046-7298>
alejandro.saiz@unison.mx

Marcelo Lomeli-Banda

Doctor en Ciencias
Profesor investigador de la Facultad de Ingeniería
Universidad Autónoma de Baja California
Mexicali, México
<https://orcid.org/0000-0003-0171-9394>
lomeli.marcelo@uabc.edu.mx



ABSTRACT

The increase in urban temperatures, driven by climate change and the expansion of gray infrastructure, has intensified the urban heat island (UHI) phenomenon, affecting thermal comfort in outdoor spaces. This study characterized the campus thermal environment at the Autonomous University of Baja California in Mexicali, one of the world's hottest cities, to identify opportunities for green infrastructure (GI) planning. The methodology included generating a high-resolution orthomosaic using an unmanned aerial vehicle to calculate the NGRDI index, in situ measurements of land surface temperature (LST) using infrared thermometers, and geospatial analysis of both variables. The results showed higher temperatures on impervious surfaces such as concrete and asphalt, while tree-covered areas presented lower values. However, some green areas with low vegetation vigor showed limited cooling capacity, highlighting the need to strengthen GI strategies.

Keywords

urban heat islands, vegetation, NGRDI, green infrastructure, planning

RESUMEN

El incremento de las temperaturas urbanas, asociado al cambio climático y a la expansión de la infraestructura gris, ha intensificado el fenómeno de isla de calor urbana (ICU), lo que ha afectado el confort térmico en espacios exteriores. Este estudio caracterizó el entorno térmico del campus de la Universidad Autónoma de Baja California en Mexicali, una de las ciudades más calurosas del mundo, con el objetivo de identificar oportunidades para la planificación de infraestructura verde (IV). La metodología incluyó la generación de un ortomosaico de alta resolución mediante un vehículo aéreo no tripulado para el cálculo del índice NGRDI, mediciones in situ de temperatura superficial (LST) con termómetros infrarrojos y el análisis geoespacial de ambas variables. Los resultados mostraron temperaturas más elevadas en superficies impermeables, como el concreto y el asfalto, mientras que las áreas arboladas presentaron valores más bajos. No obstante, se identificaron zonas verdes con bajo vigor vegetal y capacidad de enfriamiento limitada, lo que evidencia la necesidad de fortalecer las estrategias de IV.

Palabras clave

islas de calor urbanas, vegetación, NGRDI, infraestructura verde, planeación

RESUMO

O aumento das temperaturas urbanas, associado às mudanças climáticas e à expansão da infraestrutura cinza, tem intensificado o fenômeno da ilha de calor urbana (ICU), afetando o conforto térmico em espaços externos. Este estudo caracterizou o ambiente térmico do campus da Universidade Autônoma da Baixa Califórnia em Mexicali, uma das cidades mais quentes do mundo, com o objetivo de identificar oportunidades para o planejamento de infraestrutura verde (IV). A metodologia incluiu a geração de um ortomosaico de alta resolução por meio de um veículo aéreo não tripulado para o cálculo do índice NGRDI, medições in situ da temperatura da superfície (LST) com termômetros infravermelhos e a análise geoespacial de ambas as variáveis. Os resultados mostraram temperaturas mais elevadas em superfícies impermeáveis, como o concreto e o asfalto, enquanto as áreas arborizadas apresentaram valores mais baixos. No entanto, foram identificadas zonas verdes com baixo vigor vegetal e capacidade limitada de resfriamento, o que evidencia a necessidade de fortalecer as estratégias de infraestrutura verde.

Palavras-chave

ilhas de calor urbanas, vegetação, NGRDI, infraestrutura verde, planejamento

INTRODUCTION

The global acceleration of urbanization, particularly in developing countries, has led to the concentration of population in cities, where approximately 55% of the world's population currently lives (United Nations, 2018; Valavanidis, 2024). This process, combined with climate change, has intensified the urban heat island (UHI) phenomenon, worsening environmental conditions in the built environment and directly affecting population health and thermal comfort in outdoor spaces. The adverse effects of urban overheating are manifested in both psychological well-being and the perception of heat, emotional state, and ability to concentrate, as well as in associated physiological impacts, such as sunburn and other disorders related to thermal exposure (Rony & Alamgir, 2023). In this context, thermal comfort in outdoor spaces has become increasingly relevant to the quality of urban life.

UHIs are environmental phenomena characterized by higher average temperatures in urban areas than in surrounding rural areas (Garzón et al., 2024). This phenomenon is a direct consequence of human activities and the transformation of the natural landscape, in which artificial materials predominate and alter the Earth's surface's original thermal balance, increasing heat absorption and retention (Oke, 1982).

Due to rising urban temperatures and the intensification of the UHI effect, several studies have indicated that thermal comfort in urban outdoor spaces is a key element of population well-being. In urban design processes, the need to consider the thermal impact of the built environment and to promote research to improve outdoor habitability, particularly at the microclimatic scale, has been emphasized (Mandjoupa et al., 2025). The UHI is characterized by air temperature measurements, specifically from the lowest layer of the atmosphere up to the height of trees or buildings (Arnfield, 2003; Stewart, 2011). In addition to the Urban Heat Island (UHI) phenomenon, Land Surface Temperature (LST) is a fundamental variable in analyzing the surface-atmosphere energy balance. While the air temperature characterizes the UHI, the LST represents the surface temperature and is one of the main variables used to evaluate this phenomenon from a surface perspective (Schwarz et al., 2012; Krishnan et al., 2020). In this sense, it is important to distinguish between the atmospheric Urban Heat Island (UHI), associated with air temperature within the urban canopy, and the Surface Urban Heat Island (SUHI), derived from LST analysis (Voogt & Oke, 2003). The latter

enables characterization of the surface's thermal variations using remote sensing techniques, which provide spatially continuous information on urban thermal behavior.

The specialized literature indicates that for an urban space to provide adequate thermal comfort, it must meet at least three fundamental criteria: the morphological configuration of the built environment, the spatial orientation of its components, and the presence of vegetation (Yahia & Johansson, 2014). Studies such as those of Wu et al. (2024) indicate that increasing vegetation cover by 1% reduces the surface temperature of 0.099-0.1 °C in urban environments, where it has been observed that the shade generated by trees can contribute up to 80% of the total cooling effect in open spaces (Shashua-Bar & Hoffman, 2000), which consolidate vegetation as a key element in urban microclimate regulation (Declet-Barreto et al., 2013).

Vegetation plays an important role in mitigating high surface temperatures, as some of its properties, such as evapotranspiration, reduce ambient temperature. However, due to damage or stress on vegetation, environmental cooling could be reduced (Speak, 2015).

Several indices describe vegetation health, with the Normalized Difference Vegetation Index (NDVI) being the most widely used in the literature (Huang et al., 2021). Commonly, this index is obtained by using multispectral cameras mounted on Unmanned Aerial Vehicles (UAVs), also known as drones. However, this equipment tends to be expensive, and its acquisition is limited (Stamford et al., 2023). Alternatively, indices based solely on RGB bands (Red/Green/Blue) can be used to identify and distinguish vegetation and/or crops from soils or other surfaces, as well as to assess vegetation health.

Studies such as those of Macedo et al. (2025) conclude that one of the most reliable indices for detecting vegetation health based on RGB bands is the Normalized Green Red Difference Index (NGRDI), which is more readily estimated. In their study, they aimed to detect weeds in vineyards during the crop cycle. RGB images obtained from UAVs were used to evaluate several vegetation indices, with the NGRDI showing the best results since it clearly differentiated the vine and soil classes. It detected weeds more accurately than other indices.

Also, Lee & Yu (2019) conducted research to propose a method to automatically detect unhealthy and dead trees, in which the NGRDI was used as a

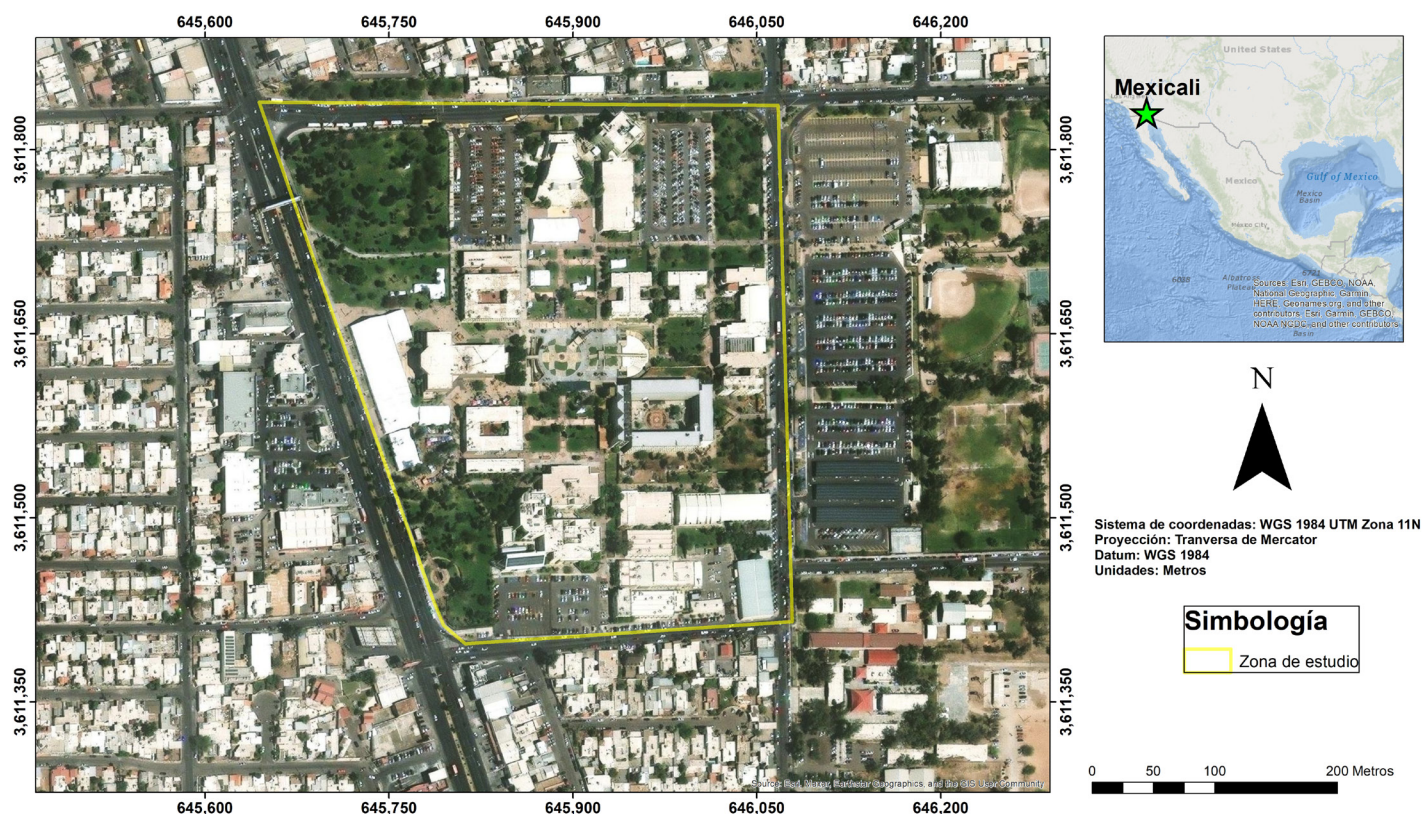


Figure 1. Location of the study area. Source: Prepared by the authors.

vegetation health index, obtaining results with a confidence level of more than 80% in the detection of dead trees, showing that the NGRDI is also an index that indicates the health of vegetation.

Therefore, this study aims to analyze the relationship between the land surface temperature (LST) and vegetation conditions using the NGRDI index on a university campus. Based on this relationship, the aim is to identify areas with high thermal stress and low plant performance to inform the planning, design, and management of green infrastructure to mitigate high LST and improve thermal comfort.

STUDY AREA

The central unit of the Autonomous University of Baja California, Mexicali campus, is located in the city of Mexicali, Baja California, Mexico, at coordinates UTM 645893 East and 3611631 North in the WGS84 coordinate system, zone 11N (Figure 1). The campus has an area of approximately 14.4 Ha, of which 24% is green area (4.3 Ha), excluding small areas such as planters. This site has extensions of key green areas for environmental well-being, which provide shade for

the university community (Gutiérrez Boneo, 2025); however, the city's climatic conditions can limit vegetation health, reducing its capacity to reduce LST.

CITY CLIMATE AND SURFACE TEMPERATURE PROBLEMS

The city has a hot desert climate, with average temperatures between 41 ° and 42 °C during July and August (Mexicali City Council, 2024). However, during heat waves, temperatures can exceed 50 °C, with 52.7 °C being the highest temperature recorded historically in the city on August 7th, 2025 (Heras, 2025), making it the city with the highest temperature recorded in Mexico and thus one of the hottest cities in the world. In addition to the region's climatic characteristics, the rapid expansion of gray infrastructure has contributed to rising surface temperatures, which amplify the UHI effect (Yang et al., 2021).

The Mexicali City Council established the local regulatory framework through the Regulation of Green Areas for the municipality of Mexicali (Mexicali City Council, 2005). In its original design, Article 11 stipulated that the construction of shopping malls

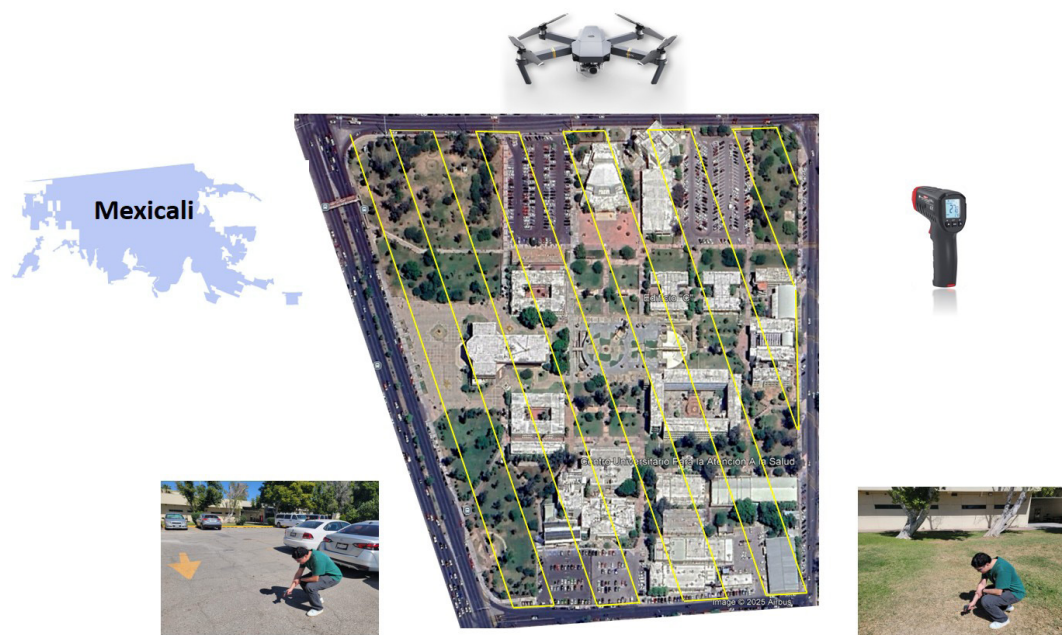


Figure 2. Work methodology. Source: Prepared by the authors.

and of construction sites with outdoor parking for more than nine cars required planting one tree for every six parking spaces. However, after the reform published in the Official Gazette of the State of Baja California in 2015, this requirement was doubled to one tree per three parking spaces, empowering the authority to deny building permits for non-compliance (Mexicali City Council, 2005; reformed in 2015). Despite this punitive measure, most parking lots in shopping malls and public spaces disregard the rule. As a result, these surfaces are directly exposed to solar radiation, which intensifies the micro-urban heat island effect and increases the thermal stress on users.

Although these regulations only establish tree planting, they do not include criteria that effectively reduce temperature and the UHI.

METHODOLOGY

In general, this project was carried out in three methodological stages (Figure 2). In the first, a high-resolution image (orthomosaic) was generated using an Unmanned Aerial Vehicle (UAV) to calculate the Red-Green Normalized Difference Index (NGRDI) and to characterize the vegetation within the university campus spatially. In the second stage, land surface temperature (LST) data were obtained via in situ measurements using infrared thermometers, following a standardized protocol to ensure consistency across records. Finally, both variables were integrated into

a geospatial analysis environment to evaluate their relationship and degree of correlation, allowing the identification of spatial patterns associated with thermal stress and plant performance.

PHOTOGRAMMETRIC FLIGHT USING UAV

The photogrammetric flight was carried out using a DJI Mavic Pro UAV and the DroneDeploy application. To configure the flight plan, the parameters shown in Table 1 were used to obtain a high-resolution image (orthomosaic) of the university campus using the Agisoft Metashape version 1.8.0 program, and, with this input, also to calculate the NGRDI.

Table 1. Photogrammetric flight configuration parameters. Source: Prepared by the authors.

Photogrammetric flight configuration	
Flight surface	15 hectares
Flight time	13:55 minutes
Flight height	80 meters
Camera position angle	90°
Percentage of overlap between photographs	80%

NGRDI CALCULATION

To calculate the NGRDI, a composition of the green and red bands from the photogrammetric flight was conducted, using the following equation (Equation 1).

$$NGRDI = \frac{GREEN - RED}{GREEN + RED} \quad (\text{Equation 1})$$

To create this band composition, ArcGIS version 10.5 and its Raster Calculator tool were used. According to the literature, this band composition yields an NGRDI index ranging from -1 to 1, with negative values associated with surfaces without vegetation cover and water bodies. In contrast, values close to 0 indicate bare soils or poor plant health. On the other hand, positive values close to 1 indicate dense and healthy vegetation (Jannoura et al., 2015).

ACQUISITION OF SURFACE TEMPERATURE DATA

To obtain surface temperature data, an in situ survey was conducted. UNI-T UT306S infrared thermometers were used. Measurements were taken at a distance of 0.10 m from the surface across the entire university campus and its different land cover types to ensure accurate data acquisition. A raster-type temperature surface was generated using ArcGIS version 10.5. The data acquisition activity was carried out on May 12th, 2025, between 1:15 pm and 2:15 pm.

EVALUATION OF THE CORRELATION BETWEEN THE NGRDI AND THE SURFACE TEMPERATURE

The Pearson correlation coefficient (r) was used to assess the statistical relationship between the NGRDI and surface temperature. This coefficient quantifies the continuous linear relationship between two numerical variables and is commonly used in remote perception studies (Rahimi et al., 2025).

The Pearson coefficient is calculated using the following expression (Equation 2):

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (\text{Equation 2})$$

Where:

r: Pearson's correlation coefficient.

x_i : the values of the NGRDI.

y_i : the values of the surface temperature.

$\bar{x}$ and $\bar{y}$: Represent the means of each variable.

n: Total number of observations.

The values of the coefficient r range between -1 and 1 (Figure 3).

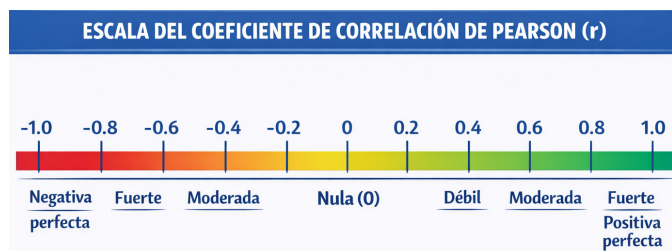


Figure 3. Pearson correlation (r) coefficient scale. Source: Prepared by the authors.

In the case study, negative values indicate an inverse relationship: the greater the vegetation health (higher NGRDI), the lower the surface temperature, whereas positive values indicate a direct relationship. Another variable considered in the analysis was the coefficient of determination (R^2), which is the square of the correlation coefficient r and represents the proportion of the variance in the dependent variable explained by the independent variable (Duke University, 2002). In this study, the dependent variable is surface temperature, while the independent variable is the NGRDI.

RESULTS

PHOTOGRAMMETRIC FLIGHT AND ORTHOMOSAIC GENERATION

A total of 297 aerial images of the university campus were obtained and processed at a flight height of 70m above ground level. With 80% overlap between photographs, an orthomosaic was generated using the Agisoft Metashape program at a spatial resolution of 5cm/pixel (Figure 4). In this image, the different materials on the campus surface are more clearly identified.

VEGETATION HEALTH ASSESSMENT BY NGRDI

By combining the RGB spectral bands, it was possible to determine the state of health of the vegetation within the university campus, as indicated by values ranging from -0.33 to 0.24, where negative values represent vegetation in poor condition and positive values represent healthier vegetation (Figure 5).

Within the campus's green areas, negative NGRDI values were identified, mainly associated with grass-covered surfaces. Field observations indicated low vegetative vigor in these areas. These areas had relatively higher surface temperatures than areas dominated by tree cover. The spatial match between negative NGRDI values and higher surface

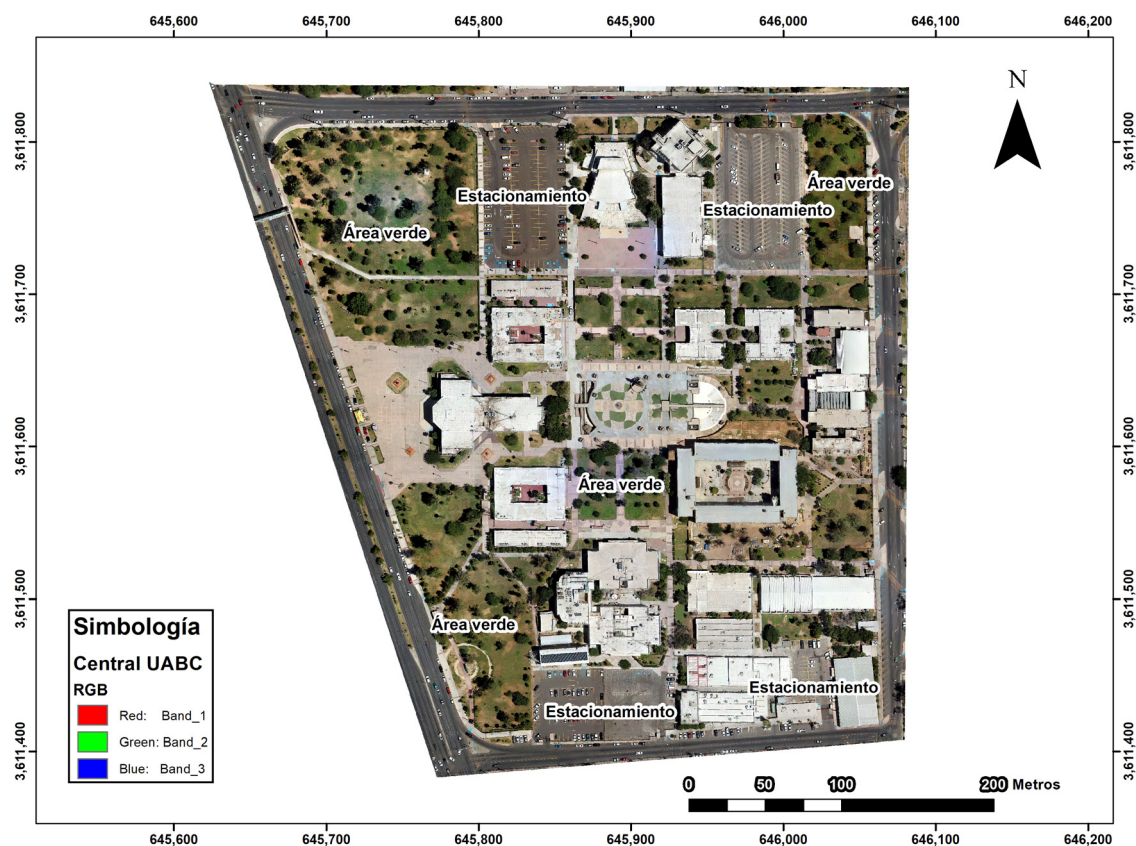


Figure 4. Orthomosaic of the university campus, spatial resolution of 5cm/pixel. Source: Prepared by the authors.

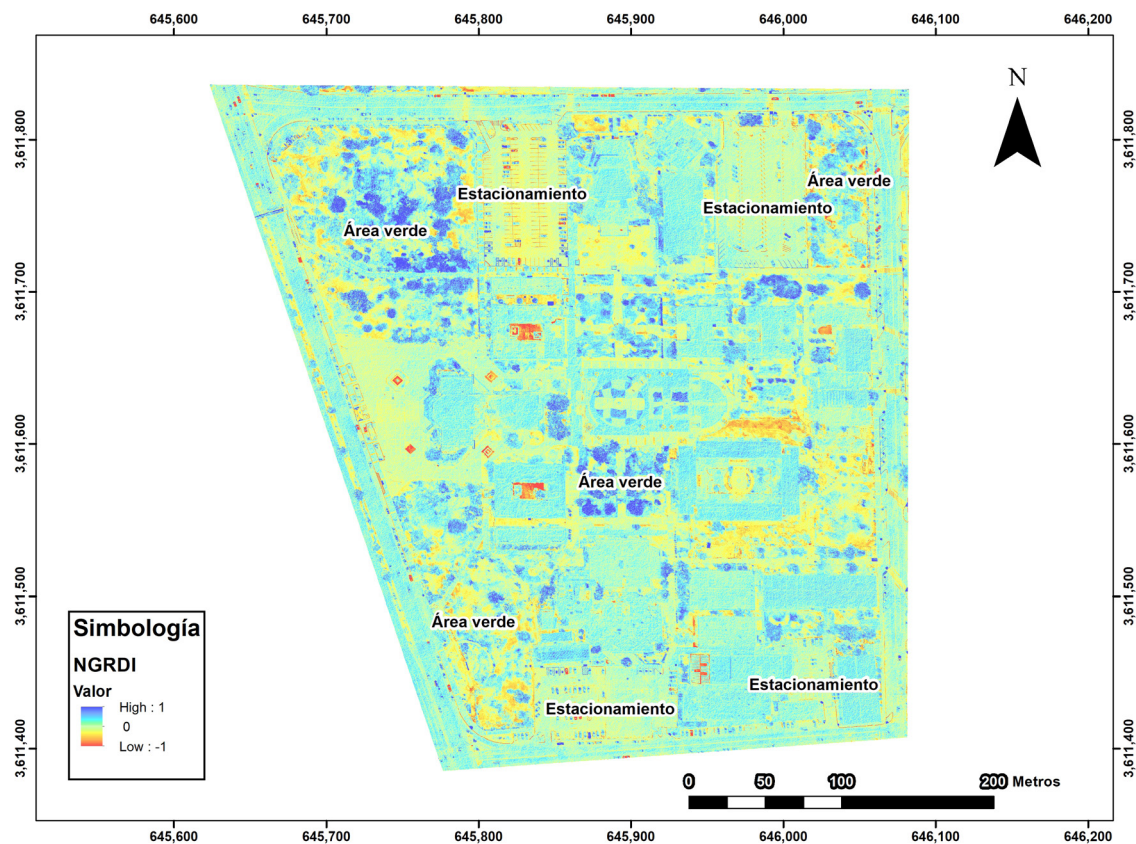


Figure 5. NGRDI map of the university campus. Source: Preparation by the authors.

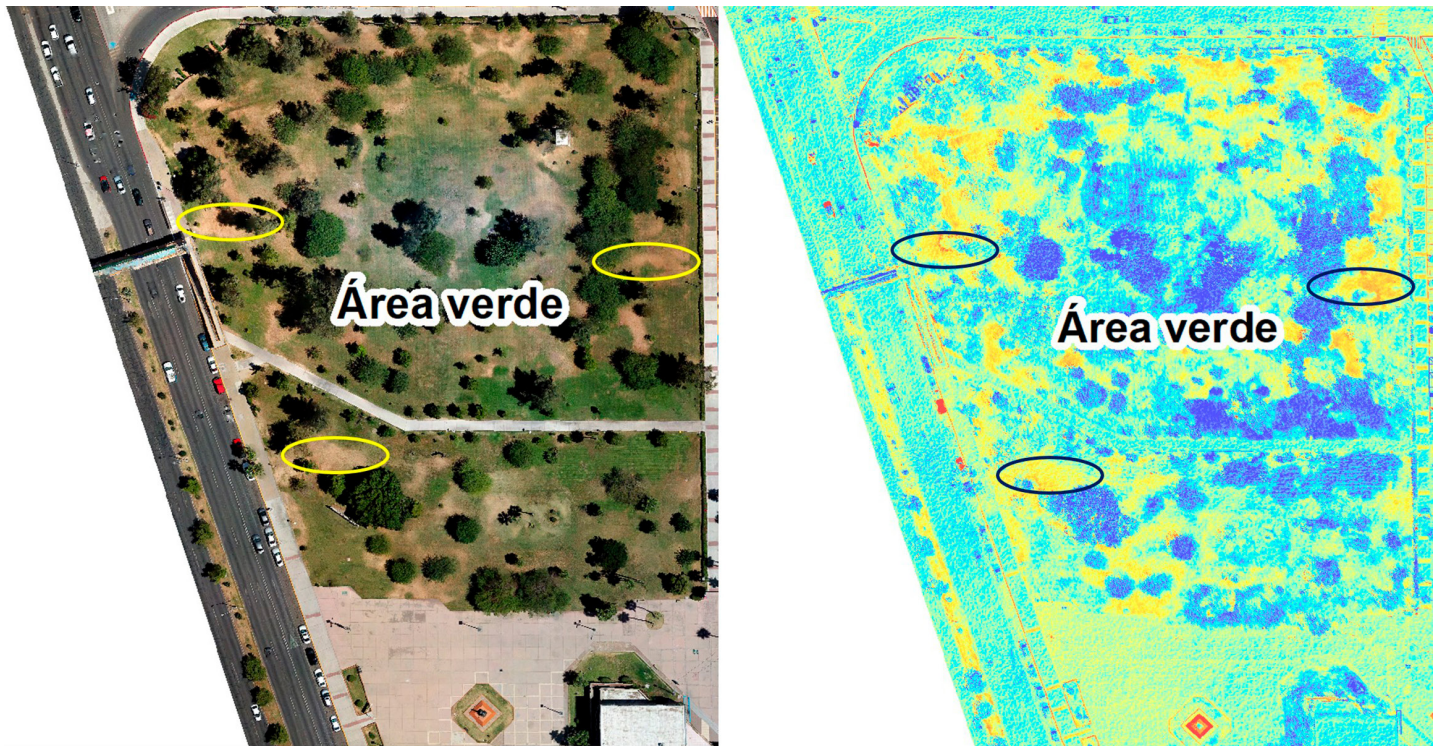


Figure 6. Example of negative NGRDI in vegetation and visual verification. Source: Prepared by the authors.

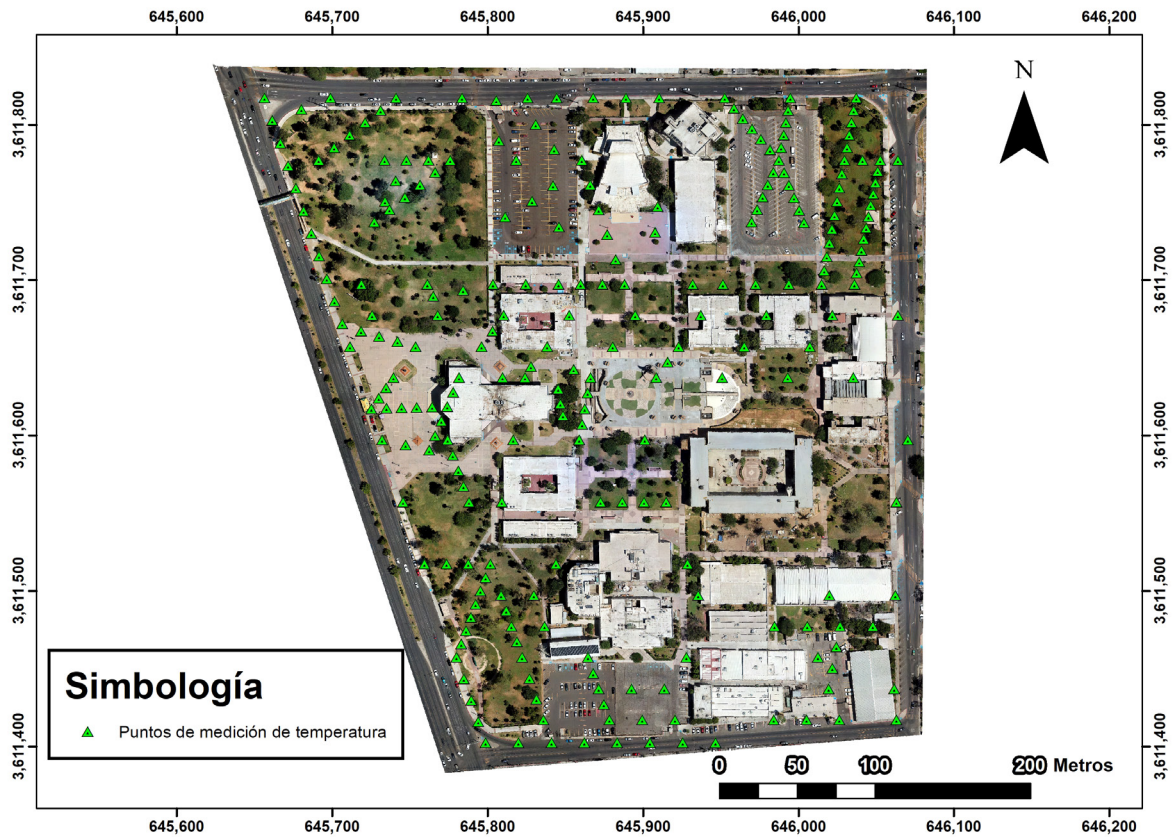


Figure 7. Distribution of temperature measurement points. Source: Prepared by the authors.

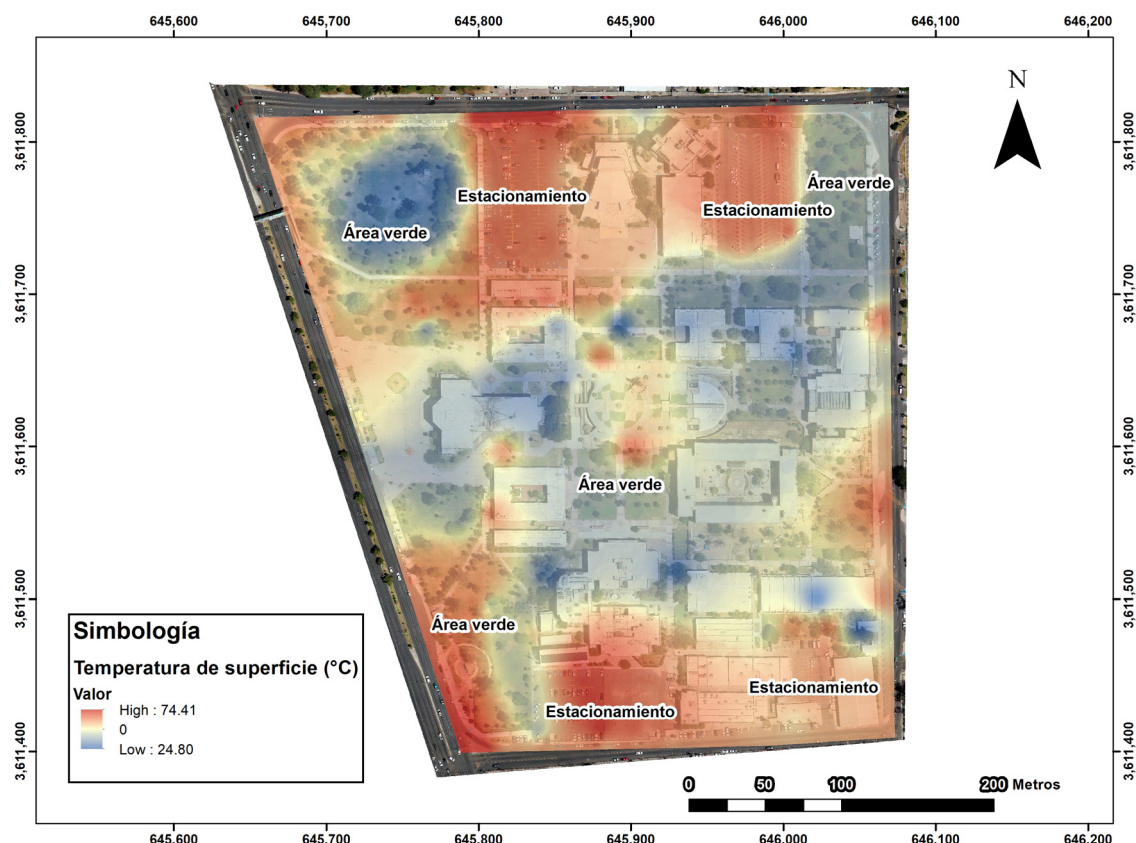


Figure 8. Surface temperature map generated using the data acquired on May 15th, 2025. Source: Prepared by the authors.

temperatures suggests reduced vegetative vigor and a limited capacity of these surfaces to mitigate thermal effects (Figure 6).

SURFACE TEMPERATURE GENERATION

A total of 246 surface temperature points of the university campus were obtained (Figure 7), and their data were used to generate a surface temperature raster. The weighted inverse distance interpolation (IDW) method was also used, resulting in a surface with a minimum temperature of around 24.8°C and a maximum of 72.4°C, as shown in Figure 8.

The minimum temperature values appeared within the green areas, specifically where the trees' shadows were. Temperature differences were observed between 5 °C and 6 °C compared to the green areas directly exposed to sunlight, which reaffirms the importance of trees for mitigating high temperatures, especially in arid and semi-arid regions.

Although the IDW method is used in spatial analysis and has been considered an effective method for temperature interpolation (Lau & Hsu, 2025), its accuracy strongly depends on the spatial distribution of the sampling points, and inaccurate results may be presented when these are irregular, especially

in environmental contexts where the data density is heterogeneous (Ohlert et al., 2023). In addition, the extreme values of the interpolated surface are restricted at the measured points, which limits the detection of real maxima and minima (Longley et al., 2005). For the case study, the heterogeneity of the points was limited due to the difficulty of accessing parts of the university campus and other factors that hindered data acquisition.

CORRELATION BETWEEN THE NGRDI AND THE SURFACE TEMPERATURE

The Pearson correlation coefficient (r) between the NGRDI and the surface temperature was -0.122, indicating a weak inverse relationship between vegetation presence and surface temperature. Although vegetation helps reduce surface temperature, the results suggest that its influence is not a dominant factor in explaining thermal variability within the university campus. The coefficient of determination (R^2) was 0.0148 (Figure 9), indicating that only 1.48% of the observed thermal variability is explained by variations in the NGRDI.

Several studies have documented a negative relationship between vegetation indices, such as the NGRDI, and the Earth's surface temperature (Anand et al., 2025; Dheeraj et al., 2025). This behavior is

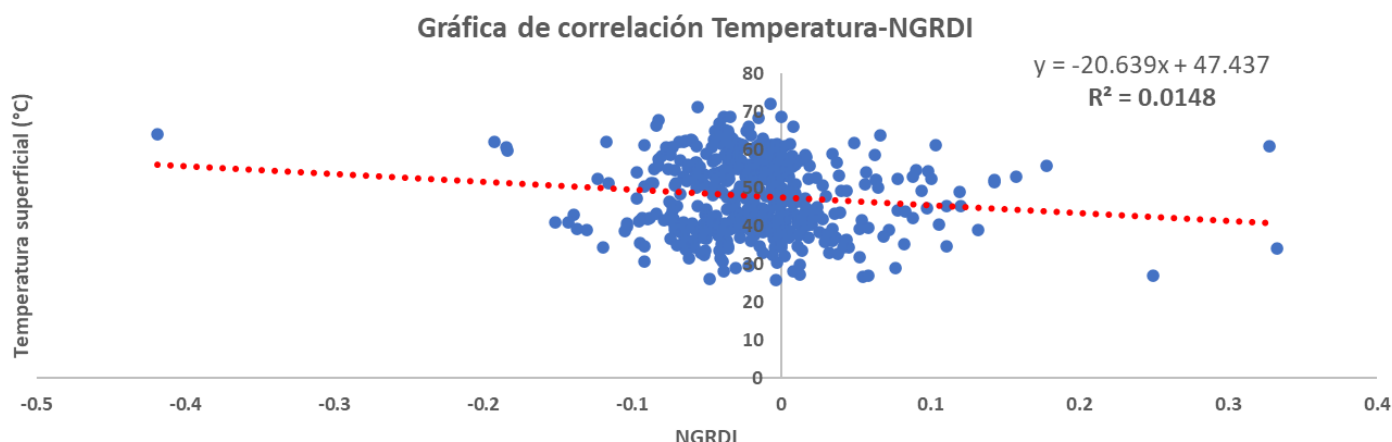


Figure 9. Comparative analysis of the correlation between surface temperature and the NGRDI. Source: Prepared by the authors.

mainly explained by the shading effects of trees and evapotranspiration processes, which influence the regulation of surface thermal storage (Yin et al., 2024). However, a weak correlation between the two variables is observed in the study area. This result could be associated with the high coverage of impermeable surfaces, such as asphalt and concrete, as well as the presence of low-vigor vegetation and bare soil. Additionally, the region's semi-arid climate may limit vegetation's ability to provide effective environmental cooling (Dashti & Khajah, 2024).

DISCUSSION

A relevant finding of this research is the identification of areas with low plant performance and high thermal stress within the university campus, particularly in the southwest and east-central areas, where negative NGRDI values close to -1 were recorded and were associated with vegetation in deficient or absent conditions. These areas coincide spatially with surfaces dominated by impermeable materials, such as parking lots, which presented the highest surface temperatures, reaching up to 71.4 °C. This behavior shows the decisive role of gray infrastructure in heat accumulation, which is also influenced by properties such as albedo, which regulates the absorption of solar radiation and contributes to increased surface temperature. In this context, several studies (Franco et al., 2025; Zhao et al., 2025) have shown that implementing permeable surfaces, combined with vegetation cover, promotes the dissipation of thermal energy through evaporative and evapotranspiration processes. However, the results obtained also show that not all vegetation contributes effectively to surface cooling. In arid environments such as Mexicali, there is a trade-

off between water conservation and thermal efficiency, since, although reforestation programs and local regulations prioritize the use of endemic species (Mexicali City Council, 2020), these present physiological adaptations aimed at reducing water loss, which limits their evapotranspiration rates and, therefore, their cooling capacity. Consequently, green infrastructure planning should not focus solely on incorporating native vegetation but on selecting functional species that consider their thermal performance. It is therefore proposed to prioritize species that, within the allowed vegetable palette, have greater cooling efficiency to optimize the balance between water efficiency and thermal mitigation capacity. This approach would allow shifting from a conventional vision of reforestation to a climate design strategy that simultaneously addresses water stress and extreme temperature conditions identified in the study area.

CONCLUSIONS

This study characterized the thermal environment of the UABC campus in Mexicali and considered variables such as land use, surface materials, surface temperature, and vegetation condition. The results allowed the identification of spatial patterns of thermal behavior within the campus and their interaction with the urban environment. The highest surface temperatures were recorded on impermeable surfaces, particularly concrete and asphalt, while the lowest values were observed in green areas, especially under the shade of trees. Although the green areas showed a general trend of surface cooling, areas where vegetation did not significantly contribute to the thermal reduction were identified, mainly in those with deteriorated

lawns and low NGRDI values. The results obtained matched those reported in the literature, where the lack of vegetation cover, poor vegetation health, and the increase in gray infrastructure increase heat absorption and reduce the environment's cooling capacity.

The trend is as expected; however, the relationship is weak due to the health and layout of the vegetation space, so one opportunity is to intervene in areas of low health with IV to correct the cooling deficit these areas currently provide.

With regard to vegetation, tree shading is one of the most important factors for urban cooling, as it decreases surface temperature by 5-6 °C, yielding better results than grass, particularly at sites of low vigor. Nevertheless, water availability and climatic conditions, such as temperature and solar radiation, affect the cooling capacity of trees; therefore, the IV should be strategically planned by prioritizing factors such as planting endemic trees in regions with the highest evapotranspiration rates. Therefore, it is advisable to conduct studies on the cooling capacities of endemic vegetation in these regions and, in turn, to develop studies focused on the design and management implications of the IV, considering variables such as land cover and use, material properties, and microclimate simulations. This will allow determining thermal comfort variables, which describe the physical state and psychological well-being experienced by the individual in their environment, thus contributing to the improvement of their quality of life.

LIMITATIONS

This study is based on a thermal analysis conducted at a specific point in time, which limits the evaluation of seasonal variability in surface temperature. However, the information collection was carried out during May 2025, a period when the city of Mexicali experiences elevated temperatures that can exceed 40 °C, enabling the characterization of the campus's thermal behavior under significant heat. It is possible that during periods of greater summer thermal intensity, surface temperatures are even higher. Also, semi-arid climatic conditions can cause water stress in vegetation, which could affect its cooling capacity. In this sense, future studies could incorporate broader temporal analyses to better understand the thermal dynamics and the role of vegetation in mitigating the urban heat island.

CONTRIBUTION OF AUTHORS CRediT:

Conceptualization, C.S.B.; Data Curation, J.M.R.G., J.A.S.R.; Formal analysis, C.S.B., J.M.R.G.; Research, W.A.R.; Methodology, W.A.R., C.S.B.; Software, W.A.R., J.M.R.G., J.A.S.R.; Validation, J.M.R.G., J.A.S.R.; Visualization, M.A.L.B.; Writing - original draft, W.A.R., C.S.B.; Writing - revision and editing, C.S. B, M.A.L.B.

ACKNOWLEDGMENTS

The authors would like to thank the Secretariat of Science, Humanities, Technology and Innovation (SECIHTI) for the grant awarded for the academic training of one of the authors. This research did not receive any other funding.

BIBLIOGRAPHIC REFERENCES

Anand, V., Kaur, S., Rajput, V. D., Minkina, T., Mandzhieva, S., Kumar, S., Sharma, A., & Kumar, S. (2025). Analyzing the spatial relationship between land surface temperature and normalized difference vegetation index using remote sensing and GIS. *Discover Geoscience*, 3(1), 65. <https://doi.org/10.1007/s44288-025-00167-w>

Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, 23(1), 1–26. <https://doi.org/10.1002/joc.859>

Ayuntamiento de Mexicali. (2005). *Reglamento de áreas verdes para el municipio de Mexicali, Baja California*. Gobierno Municipal de Mexicali. <https://www.ordenjuridico.gob.mx/Estatal/BAJA%20CALIFORNIA/Municipios/Mexicali/REG01.pdf>

Ayuntamiento de Mexicali. (2020). *Guía de forestación para el municipio de Mexicali, baja California*. Gobierno Municipal de Mexicali. <https://www.scribd.com/document/610318541/2021-Guia-Municipal-de-Forestacion-para-el-Municipio-de-Mexicali-2021>

Ayuntamiento de Mexicali. (2024). *Atlas de Riesgos del Municipio de Mexicali, B.C. [Actualización 2023]*. Universidad Autónoma de Baja California [UABC]. Unidad Municipal de Protección Civil. <http://www.mexicali.gob.mx/transparencia/administracion/atlas/pdf/0.pdf>

Dashti, A., & Khajah, M. (2024). Urban green areas and their impact on land surface temperature in semi-arid environments: a case study in Kuwait. *GeoJournal*, 89, 86. <https://doi.org/10.1007/s10708-024-11079-6>

- Declet-Barreto, J., Brazel, A. J., Martin, C. A., Chow, W. T., & Harlan, S. L. (2013). Creating the park cool island in an inner-city neighborhood: heat mitigation strategy for Phoenix, AZ. *Urban Ecosystems*, 16(3), 617-635. <https://doi.org/10.1007/s11252-012-0278-8>
- Dheeraj, V. P., Rai, A. K., Yadav, A. K., Sonkar, S., Maurya, A., Chaudhary, A., & Chaudhary, P. (2025). Spatiotemporal analysis and correlation of surface temperature, vegetation cover, and water index using remote sensing and GIS techniques in Ambedkar Nagar, India. *Discover Environment*, 3(1), 232. <https://doi.org/10.1007/s44274-025-00438-w>
- Duke University. (2002). *STA102: Correlation and regression – The coefficient of determination*. Department of Statistical Science, Duke University.
- Jannoura, R., Brinkmann, K., Uteau, D., Bruns, C., & Joergensen, R. G. (2015). Monitoring of crop biomass using true colour aerial photographs taken from a remote controlled hexacopter. *Biosystems Engineering*, 129, 341-351. <https://doi.org/10.1016/j.biosystemseng.2014.11.007>
- Franco, E., Ghisi, E., Vaz, I. C. M., & Thives, L. P. (2025). Permeable Pavements: An Integrative Review of Technical and Environmental Contributions to Sustainable Cities. *Water*, 17(22), 3323. <https://doi.org/10.3390/w17223323>
- Gutiérrez Boneo, M. M. (10 de junio de 2025). *El cuidado de áreas verdes: Clave para el bienestar ambiental*. Gaceta UABC. Universidad Autónoma de Baja California. <https://gaceta.uabc.mx/el-cuidado-de-areas-verdes-clave-para-el-bienestar-ambiental>
- Garzón, J., Molina Sánchez, I., & Jiménez Cleves, G. (2024). Evaluación del fenómeno de la isla de calor urbano en Cartago, Colombia: tendencias de factores ambientales en los últimos 20 años. *Encuentro Internacional de Educación en Ingeniería ACOFI*. <https://doi.org/10.26507/paper.3712>
- Heras, A. (8 de agosto de 2025). *Mexicali, BC, rompe récord de temperatura con 52.7 grados Celsius*. La Jornada. <https://www.jornada.com.mx/noticia/2025/08/08/estados/mexicali-bc-rompe-record-de-temperatura-con-527-grados-celsius>
- Huang, S., Tang, L., Hupy, J. P., Wang, Y., & Shao, G. (2021). A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. *Journal of Forestry Research*, 32(1), 1-6. <https://doi.org/10.1007/s11676-020-01155-1>
- Krishnan, P., Meyers, T. P., Hook, S. J., Heuer, M., Senn, D., & Dumas, E. J. (2020). Intercomparison of in situ sensors for ground-based land surface temperature measurements. *Sensors*, 20(18), 5268. <https://doi.org/10.3390/s20185268>
- Lau, T.-K., & Hsu, H.-C. (2025). Urban Heat Island Effect and Unequal Temperature-Related News Attention in Taiwan's Major Cities. *Urban Science*, 9(10), 417. <https://doi.org/10.3390/urbansci9100417>
- Lee, S., & Yu, B.-H. (2019). Automatic detection of dead tree from UAV imagery. *Coordinates*, 15(4), 36-39. <https://mycoordinates.org/pdf/apr19.pdf>
- Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2005). *Geographical information systems and science*. John Wiley & Sons.
- Macedo, F. L., Nóbrega, H., de Freitas, J. G., & Pinheiro de Carvalho, M. A. A. (2025). Assessment of vegetation indices derived from UAV imagery for weed detection in vineyards. *Remote Sensing*, 17(11), 1899. <https://doi.org/10.3390/rs17111899>
- Mandjoupa, L. K., Behera, P., Roman, K. K., Azam, H., & Denis, M. (2025). Street-Level Sensing for Assessing Urban Microclimate (UMC) and Urban Heat Island (UHI) Effects on Air Quality. *Environments*, 12(6), 184. <https://doi.org/10.3390/environments12060184>
- Ohlert, P. L., Bach, M., & Breuer, L. (2023). Accuracy assessment of inverse distance weighting interpolation of groundwater nitrate concentrations in Bavaria (Germany). *Environmental Science and Pollution Research*, 30(4), 9445-9455. <https://doi.org/10.1007/s11356-022-22670-0>
- Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1-24. <https://doi.org/10.1002/qj.49710845502>
- Rahimi, E., Dong, P., & Jung, C. (2025). Global NDVI-LST correlation: Temporal and spatial patterns from 2000 to 2024. *Environments*, 12(2), 67. <https://doi.org/10.3390/environments12020067>
- Rony, M. K. K., & Alamgir, H. M. (2023). High temperatures on mental health: Recognizing the association and the need for proactive strategies—A perspective. *Health Science Reports*, 6(12), e1729. <https://doi.org/10.1002/hsr2.1729>
- Schwarz, N., Schlink, U., Franck, U., & Großmann, K. (2012). Relationship of land surface and air temperatures and its implications for quantifying urban heat island indicators—An application for the city of Leipzig (Germany). *Ecological indicators*, 18, 693-704. <https://doi.org/10.1016/j.ecolind.2012.01.001>
- Shashua-Bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street: An empirical model for predicting the cooling effect of urban green areas with trees. *Energy Buildings* 31(3), 221-235. [https://doi.org/10.1016/S0378-7788\(99\)00018-3](https://doi.org/10.1016/S0378-7788(99)00018-3)
- Speak, A. (2015). 12-Influence of vegetation damage on urban cooling effects in F. Pacheco-Torgal, J.A. Labrincha, L.F. Cabeza, C.-G. Granqvist (Eds.), *Eco-Efficient Materials for Mitigating Building Cooling Needs* (pp. 325-347). Woodhead Publishing. <https://doi.org/10.1016/B978-1-78242-380-5.00012-1>
- Stamford, J. D., Violet-Chabrand, S., Cameron, I., & Lawson, T. (2023). Development of an accurate low cost NDVI imaging system for assessing plant health. *Plant Methods*, 19(1), 9. <https://doi.org/10.1186/s13007-023-00981-8>
- Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, 31(2), 200-217. <https://doi.org/10.1002/joc.2141>

United Nations. (16 de mayo de 2018). *2018 Revision of World Urbanization Prospects*. United Nations, Department of Economic and Social Affairs. <https://www.un.org/en/desa/2018-revision-world-urbanization-prospects>

Valavanidis, A. (2024). *Half of the Global Population Lives in MegaCities. Megacities are hotspots for slums, GHG emissions, toxic air pollution, climate change, deteriorating water and soil quality*. https://www.researchgate.net/publication/379655450_Half_of_the_Global_Population_Lives_in_MegaCities_Megacities_are_hotspots_for_slums_GHG_emissions_toxic_air_pollution_climate_change_deteriorating_water_and_soil_quality

Voogt, J. A., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment*, 86(3), 370-384. [https://doi.org/10.1016/S0034-4257\(03\)00079-8](https://doi.org/10.1016/S0034-4257(03)00079-8)

Wu, B., Zhang, Y., Wang, Y., He, Y., Wang, J., Wu, Y., Lin, X., & Wu, S. (2024). Mitigation of urban heat island in China (2000–2020) through vegetation-induced cooling. *Sustainable Cities and Society*, 112, 105599. <https://doi.org/10.1016/j.scs.2024.105599>

Yahia, M. W., & Johansson, E. (2014). Landscape interventions in improving thermal comfort in the hot dry city of Damascus, Syria—The example of residential spaces with detached buildings. *Landscape and Urban Planning*, 125, 1-16. <https://doi.org/10.1016/j.landurbplan.2014.01.014>

Yang, J., Ren, J., Sun, D., Xiao, X., Xia, J. C., Jin, C., & Li, X. (2021). Understanding land surface temperature impact factors based on local climate zones. *Sustainable Cities and Society*, 69, 102818. <https://doi.org/10.1016/j.scs.2021.102818>

Yin, Y., Li, S., Xing, X., Zhou, X., Kang, Y., Hu, Q., & Li, Y. (2024). Cooling benefits of urban tree canopy: A systematic review. *Sustainability*, 16(12), 4955. <https://doi.org/10.3390/su16124955>

Zhao, J., Lu, J., Ge, J., Fan, Y., Wang, H., Gu, M., Xue, Y., Zhao, Y., Lv, G., Lin, H., Zhao, K., & Luo, X. (2025). Influences of permeable pavements with different hydraulic properties on evaporative cooling and outdoor thermal environment: Field experiments. *Building and Environment*, 270, 112525. <https://doi.org/10.1016/j.buildenv.2025.112525>

