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ORIGINAL STUDY

Comparative Assessment of Land Surface Temperature in Urbanized Areas of the Saudi Arabia

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ABSTRACT

Land Surface Temperature (LST) has become a critical urban climate concern due to rapid urbanization and land cover transformation in Saudi Arabian cities. This study aimed to analyze the spatial and temporal variability of LST in three climatically distinct cities encompassing Riyadh (hot desert), Dhahran (hot humid), and Abha (cold desert) over the summer months (May to September) from 2017 to 2021. LST was retrieved through the RSLab Landsat LST web application. A total of 80 samples per year were compiled for each city using a structured sampling approach, and results were aggregated using the RS-LST Aggregation Framework (RSLAF). The results revealed that Riyadh's LST reached a maximum of 53.0°C in 2021 and a minimum of 0.0°C in 2019, showed sharp thermal contrasts and a widening diurnal temperature range. Dhahran exhibited the highest thermal stress, with maximum LST rising steadily from 54.7°C in 2017 to 60.6°C in 2021, and minimum temperatures increased from 29.2°C to 44.7°C, indicated strong heat retention. In contrast, Abha remained significantly cooler, with maximum LST peaking at 42.2°C in 2020 and falling to 33.0°C in 2021, while minimum temperatures fluctuated between 7.0°C and 20.0°C. These findings signified the need for reflective materials, urban greenery, and climate-adaptive design in urban planning. Scientifically, the study demonstrated a reproducible LST retrieval and aggregation framework for urban climate analysis, while practically, it provided data-driven insights to guide sustainable development and heat mitigation strategies in arid and semi-arid cities.

Keywords: Remote sensing techniques, Urban climate variability, Emissivity correction, Thermal anomaly analysis, Spatial temperature modeling

1. Introduction

1.1. Research background

The exterior temperature of the earth's surface constitutes the LST. Worldwide the weather has increasingly changed due to urbanization and anthropogenic activities. Urban areas are mostly affected by heat island-related problems [1]. LST is also referred to as standard surface-air temperature measured by a shielded thermometer 1–2 m above a plane and ventilated earth surface. However, LST is a good indicator of the energy balance at the surface because it is one of the key parameters in the physics of land-surface processes [2]. LST is a substantial flexible in the climate system of the Earth. It impacts the timing and rate of plant growth and defines processes such as the exchange of water and energy between the atmosphere and dry land [3]. Similar to the documented links between land use changes and hydrological stress observed in Kabul, Afghanistan, where urban expansion significantly influenced both groundwater depletion and thermal patterns, urbanization in Saudi cities also plays a critical role in shaping surface temperature dynamics [4]. LST serves as a key indicator of thermal conditions within

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urban environments, reflecting the balance between incoming solar radiation, surface properties, and heat exchange processes. In a desert environment, rising LST and the formation of urban heat island will have tremendous impacts on health conditions especially in the case of the children, elderly, and the poor residents of the city [5]. These three regions were selected based on their distinct climate designations within the KSA: Riyadh exemplifies a hot desert climate [6], Al-Dharan embodies a hot and humid climate [7], and Al-Abha demonstrates a cold desert climate [8]. These cities were also chosen because of their strategic national importance: Riyadh as the political and administrative capital with rapid urban expansion, Dhahran as an oil industry hub in the Eastern Province, and Abha for its high-altitude climate and ecological significance in the southwest region. The goal is to offer light on how climate influences urban thermal conditions. The objective is to shed light on how climate affects urban thermal conditions and identify regionally specific patterns and trends by analyzing LST data in these disparate climate zones. The five years that will be covered by the analysis are 2017 through 2021. To accommodate for seasonal and meteorological fluctuations, it will cover the five-month period from May to September. This covers both the hot and cold months. Notwithstanding the topic's importance, little is known about the dynamics of LST in the various metropolitan zones of the Kingdom of Saudi Arabia. While a lot of studies have been done all over the globe to look into dissimilarities in LST in municipal areas, not much of it has focussed on the certain environmental and meteorological conditions that are present in the KSA. To try to close this disparity, the study will examine LST in various Saudi Arabian regions, including Abha, Al-Dhahran, and Riyadh. The study will also employ a complete analysis of pertinent literature on LST dynamics and urbanization trends in the KSA and other related domains to accomplish this.

The research will include various studies that use remote sensing data and statistical modelling methods to investigate variations in LST. It will also use remote sensing data from Landsat 8 photography, with LST calculated using Rs Lab website [9]. While Landsat 8 data enable high spatial resolution studies of LST, emissivity data from MODIS improves the accuracy and reliability of LST analysis across the research areas. The aim is to enhance understanding of LST dynamics in the urban regions of KSA, significantly impacting urban planning and management. This study also attempts a comparative analysis of LST in various urbanized regions of the Kingdom by comparing LST across climatic zones and urban centers.

1.2. Literature review

The study of LST is essential in urban areas. This study has garnered significant attention due to its importance for public health, urban expansion, and environmental sustainability. In recent decades, advancements in remote sensing (RS) technology have allowed researchers to monitor and analyze LST changes with unprecedented precision and detail. This comprehensive literature review covers data from multiple studies, examining various approaches, findings, and limitations related to different metropolitan settings. LST differences are mostly triggered by urbanization, many studies have shown how built-up regions, vegetation cover, and water bodies affect LST. RS technology, mostly satellite imagery, has seemed like a valuable tool for monitoring and evaluating LST dynamics over large spatial sums. Studies such as [10, 11], have used satellite data to analyze temporal trends in LST, identify hotspots of urban heat, and evaluate the efficacy of mitigation scenarios. Moreover, the growth of innovative algorithms and modeling techniques, as shown in simplified the downscaling of LST data, enabling scholars to obtain fine-scale temperature guesses for dense areas [12, 13]. While RS offers extraordinary visions into LST dynamics, several challenges and limitations endure. Matters such as sensor calibration, atmospheric correction, and spatial resolution can introduce uncertainties in LST calculations, as discussed in these studies [14, 15]. Moreover, the complex interactions between land cover, land use, and meteorological issues necessitate integrated approaches for accurate LST modeling and prediction, as emphasized in these studies [16, 17].

Additionally, to its environmental implications, LST has significant suggestions for public health, particularly in city areas with high population density. Many research such as [18, 19] demonstrated the association between elevated LST and adverse health consequences, including heat-related illnesses and mortality. Therefore, there is a growing appreciation of the need for proactive measures to stop UHI and improve urban resilience to extreme heat events, as focused in these paper [20, 21]. The study of LST in urban areas represents a multi-layered research domain with inferences for the environment. While RS technology has revolutionized our ability to monitor and analyze LST subtleties, ongoing research efforts are needed to address existing challenges and limitations. By mixing inter-disciplinary methods and leveraging improvements in technology, scientists can contribute to the development of effective strategies for mitigating UHI and indorsing sustainable built-up development in the face of climate change.

These studies [22, 23] clarified the complex relationship between land use/land cover patterns and LST, highlighting the role of rapid growth in making worse UHI effects. By engaging geospatial techniques and RS algorithms, researchers have been able to quantify the extent of LST changes and assess their impact on urban microclimates. Besides, comparative analyses of diverse retrieval algorithms, as established in [24, 25] provided valuable insights into the strengths and boundaries of existing methodologies, flooring the way for enhanced accuracy in LST estimation. In addition, the application of advanced machine learning techniques, such as artificial neural networks (ANNs) and geographically weighted regression (GWR), which has made it possible for experts to downscale and map LST data at a finer resolution. [26, 27], Showcased the efficacy of these approaches in capturing localized variations in LST and identifying potential strategies for mitigating urban UHI. Therefore, studies on the impact of geometry on LST retrieval, as covered in [28, 29], highlighted the need of taking surface features and atmospheric variables into consideration when estimating temperature. As the mandate for high-quality LST data continues to raise, the evaluation and validation of satellite-derived products have emerged as critical components of RS research. Articles like [30, 31] have assessed the precision and reliability of LST products derived from several satellite sensors, showing the necessity of comprehensive validation procedures and supporting datasets. Additionally, thorough literature reviews, typified by [32, 33] provided comprehensive summaries of the advanced in LST research, identifying gaps in knowledge and suggesting future research directions.

Continuing the exploration of LST dynamics and its accusations, current research endeavours have extended into various geographical contexts and methodological approaches, aiming to improve understanding of urban thermal environments and inform effective mitigation plans. In many studies like [34] has introduced original methodologies for characterizing the spatiotemporal patterns of LST through time series clustering, offering valuable insights into the heterogeneous dynamics of UHI. By leveraging advanced clustering algorithms and RS data, academics have been able to distinguish latent patterns of LST variation and identify key drivers shaping urban microclimates. In parallel, efforts to assess the relationship between local climatic zones (LCZs) and land surface temperature, as exemplified by [35] underscored the importance of considering local environmental contexts in urban heat island studies. Further, recent improvements since 2022 have improved the precision and application of LST assessments. For example in [36] nonparametric correlation analysis was utilized to identify the best land attributes for creating Machine Learning (ML) models and predicting LST. The results revealed that Kuala Lumpur's LST has risen to 2.2°C between 2013 and 2023, caused by urban expansion and the subsequent UHI effect. Similarly, [37] demonstrated the benefits of integrating AI-enhanced downscaling methods to refine MODIS LST data to 100 m resolution, improving its usability for localized urban planning. Through the integration of GIS and RS techniques, researchers have clarified the complex interaction between land surface features and thermal dynamics, helping targeted involvements for climate-resilient urban planning. Similar approaches have also been applied in Iraq to project future temperature and precipitation trends under climate change scenarios [38].

Moreover, studies such as [39, 40], shed light on the geometry effects on LST recovery, stressing the need for healthy methodologies to account for surface geometry and atmospheric circumstances. By purifying existing retrieval algorithms and validation etiquettes, scientists have advanced the accuracy and reliability of satellite-derived LST products, enhancing their usefulness in various applications reaching from urban planning to environmental checking. In short, the literature review highpoints several vital limitations and research gaps that underline the need for further investigation into LST undercurrents in urban areas of the KSA. These include a absence of localized studies focusing specifically on urbanized areas in KSA, which bounds the generalize form of findings to the region. Methodological differences observed across studies may lead to irregularities in results, delaying the establishment of beneficial conclusions. Likewise, there is a notable gap in research speaking the exclusive climatic conditions of dry and semi-arid regions like those predominant in KSA, which may influence the pertinence of existing models and findings. Challenges related to the limited accessibility of local environmental datasets further hamper comprehensive analyses. As well, while some research identified the UHI result as a anxiety, there is a shortage of research explaining these findings into tortious policy measures. Addressing these gaps is essential for forward our understanding of LST variations in KSA's urban environments and notifying evidence-based policies for mitigating UHI effects and promoting sustainable urban development in the region. It also highlights global studies on LST, emphasizing the effects of urbanization, mitigation initiatives, and advances in retrieval technologies. Key findings include vegetation loss, such as a 3,470 hectare decline in Indonesia, which contributes to rising temperatures, as well as the effectiveness of green infrastructure, which reduced LST by up to 4°C in Iran. Comparative studies assessed methods such as SWA and RTE for LST accuracy, with errors of less than 1°C. In India, LST increased by 0.34°C/year in winter and 0.55°C/year in summer due to UHI. The studies illustrate the vital importance of remote sensing technologies, such as MODIS, Landsat, and UAVs, in enhancing LST analysis and informing sustainable urban planning (Table 1).

1.3. Research motivation and contribution

The impetus for this study derives from growing worries about the Urban Heat Island (UHI) impact in rapidly urbanizing portions of the Kingdom of KSA [43]. LST aids in monitoring surface water temperatures, evaporation rates, and heat exchange in rivers, lakes, and reservoirs. High LSTs in cities during summer can raise cooling energy demand by 15–30%, costing billions of dollars in additional energy usage each year and would cost consumers $1.2 to $2.1 billion [44]. Thus, Riyadh, the capital with a population of over 6.5 million, demonstrates the intensity of urban expansion and its thermal implications. Elevated LST in densely populated urban areas can have a substantial impact on local weather, energy consumption, and public health [45]. Dhahran, a strategic oil city, is likewise subjected to severe summer heat as urbanization continues. Abha, despite its warmer climate, offers a contrasting high-altitude location with ecological or tourism significance, making it a good comparison point in this multi-regional study.

Green roofs and tree planting projects can lower LST by 2–4°C, as proven by research in cities like Singapore and New York [3]. The findings of this study are projected to make a substantial contribution to the domains of urban planning and environmental management by providing data-driven insights that might inform sustainable urban design practices and heat mitigation measures. This would allow policymakers and urban planners to create localized interventions that improve the livability and sustainability of urban settings, which is crucial in an area with over 34 million people and unparalleled urban growth.

1.4. Research objectives

The purpose of this study was to look at the factors that influence the geographical and temporal variability of the KSA's different climate zones. The research was built around three main objectives: (i) To analyze the LST of each region using remote sensing data, providing a comprehensive and dynamic overview of temperature variations; (ii) to compare the LST variations within these regions, identifying patterns and anomalies in temperature distribution; and (iii) to formulate recommendations based on these findings. Therefore, these guidelines will guide urban planning and environmental policies targeted at reducing UHI effects and enhancing thermal comfort in Saudi Arabia's urbanized areas. This method will not only shed light on the relationship between urbanization and LST but will also aid in the development of regional strategies for long-term urban growth.

2. Material and methods

2.1. Models development

In the development of models for this study, the process began with an initial review of electronic sources and literature to identify gaps in existing research and formulate objectives, focusing on the unique climatic zones of Riyadh, Al Dhahran, and Abha within the Saudi Arabia region. Following the literature review, the study area was defined, and data collection was systematically planned and executed using RsLab to gather LST data. Specific input data parameters such as polygon definitions for the study areas, time frames spanning several months and years, and Landsat 8 imagery alongside emissivity data were meticulously processed. This comprehensive data processing involved detailed analysis and comparisons to discern patterns and variations in LST across the different climatic zones. The culmination of this process, illustrated in the models development flowchart (Fig. 1), led to the synthesis of findings, drawing conclusions, and formulating recommendations for effective urban planning and climate adaptation strategies.

2.2. Study area

Originally known as the Hajr desert settlement, KSA's capital and busiest city, Riyadh, was first mentioned in writing in the fourteenth century. The city has desert-like weather, with long, scorching summers and mild, brief winters. Riyadh is situated at 24°, 38′ N and 46°, 43′ E, in the center of the Arabian Peninsula, on the eastern portion of the Najd plateau (Fig. 2). The elevation is approximately 2,007 feet (612 meters) above mean sea level. Visitors are drawn to Riyadh by its contemporary skylines, cultural attractions like the National Museum, and historical sites like the Masmak Fortress. Archaeological sites such as the Al-Diriyah and the Antiquities Museum at King Saud University provide limited but insightful observations into the ancient history of the region.

Table 1. Brief overview of relevant research.

Study focus	Key findings	Methods used	Region	Year	Reference
The study aims to monitor and estimate LST (Land Surface Temperature), to understand the effects of urban development on temperature variations.	Vegetation cover shrank by 3,470 hectares, while urban areas expanded by 1,509 hectares over four years. Although the maximum temperature slightly dropped from 32°C in 2015 to 29°C in 2019, moderate-to-high temperature zones grew, reflecting the impact of less greenery and urban growth.	Landsat 8 TIRS (Thermal Infrared Sensor) data was analysed using vegetation and temperature indices to calculate LST values and assess changes in land use.	Makassar, South Sulawesi, Indonesia	2021	[24]
Urban sprawl, urban heat island (UHI), vegetation and land use impact	Urban expansion increases UHI; vegetation reduces temperature; central Isfahan is the hottest	Landsat ETM (Enhanced Thematic Mapper) imagery (1990–2019), LST, NDVI (Normalized Difference Vegetation Index), land use and urban growth analysis	Isfahan, Iran	2024	[41]
Evaluated different algorithms for retrieving LST from Landsat-8 imagery considering seasonal variations.	SWA performed best in Shanghai's hot, humid summers, while RTE (Radiative Transfer Equation), SWA (Split-Window Algorithm), and SCA (Single-Channel Algorithm) were more reliable in dry winters. LST retrieval accuracy was highest for vegetation, wetlands, and water bodies.	Compared four algorithms (RTE, MWA (Mono-Window Algorithm), SWA, SCA) using Landsat-8 data. Validated results with meteorological station data and the MOD11A2 product.	Shanghai, China	2021	[26]
Developed a downscaling technique to improve the resolution of MODIS satellite's low-resolution (1000 m) LST data using vegetation indices.	NDVI showed the strongest correlation with LST across all seasons, outperforming SAVI (soil-adjusted vegetation index) and fc. The model accurately predicted LST at 200-m resolution with errors below 1°C, suitable for applications like fire detection and urban monitoring.	Used statistical regression with MODIS vegetation indices (NDVI, SAVI, fc) to downscale LST. Validated results with thermal data logger measurements.	MNIT Jaipur, India	2020	[27]
Analysed the LST changes over three decades (1984–2016), using satellite imagery to assess urbanization's impact.	LST showed a parabolic increase over the years. Remote sensing methods were validated with ground data, showing an average bias of ±0.31, confirming their reliability for large-scale temperature mapping.	Utilized Landsat thermal infrared (TIR) bands and processed data in Idrisi and ArcGIS. Validated satellite-derived LST with ground meteorological data for accuracy.	Akoka Lagos State, Nigeria	2018	[28]
Assessed the accuracy of LST data from UAV (Unmanned aerial vehicle) thermal infrared sensors and Landsat 8 satellite, validated against in situ measurements for agricultural and environmental planning.	UAV imagery demonstrated higher accuracy (R^2: 0.89–0.90, RMSE: 0.70–1.07°C) than Landsat LST (R^2: 0.70–0.73, RMSE (Root-mean-square error): 0.78°C). A strong negative correlation was observed between LST and soil water content (−0.85 to −0.86). UAVs provided detailed localized insights missed by lower-resolution satellite data.	Collected LST data using UAV thermal sensors, Landsat 8 imagery, and in situ thermometers. Geo-referenced UAV and satellite imagery using Ground Control Points (GCPs) and compared results using regression and correlation analysis.	Jiangsu, China	2022	[29]

(Continued)

Table 1. Continued

Study focus	Key findings	Methods used	Region	Year	Reference
Analysed the relationship between land use changes and rising LST due to rapid urbanization from 1991 to 2017 using remote sensing and GIS.	Built-up areas grew from 1.85% in 1990 to 21.49% in 2017, while vegetation dropped by half. Minimum temperatures increased, especially in newly developed urban zones. Unplanned urban growth caused noticeable temperature differences between urban and peri-urban areas, fuelling urban heat islands.	Used Landsat data to compute land use through supervised learning and LST through the mono-window algorithm, validated with the modified emissivity method. Spatial analysis was performed using GIS.	Tamil Nadu, India	2020	[30]
This study investigates the relationship between LST and Local Climatic Zones (LCZs) in Sriniketan-Sanniketan Planning Area (SSPA), focusing on urban heat island effects.	LST increased by 0.34°C/year in winter and 0.55°C/year in summer, with significant variation across LCZs. The maximum and minimum LST were recorded in April and January, respectively. Proper urban planning and balancing land use can regulate LST impacts.	GIS and remote sensing techniques were used to analyse LST data, and the Urban Thermal Field Variance Index (UTFVI) was employed to assess the surface urban heat island effect.	West Bengal, India	2020	[32]
This study analyses the global trends in the use of MODIS LST data across various fields from 2009 to 2018.	MODIS LST data applications have steadily increased, covering 19 subject areas, with the most common uses in urban heat island studies, air temperature mapping, soil moisture, and drought monitoring.	The study analysed 529 articles from 159 journals in the Scopus database, examining trends and applications of MODIS LST data across multiple disciplines.	Systematic literature review	2018	[35]
Urban heat islands, high-resolution LST retrieval, data fusion.	$R^2 = 0.94$, RMSE = 0.88 K, outperformed ML methods	High-Resolution Thermal Fusion (HRTF), statistical downscaling, split-window algorithm.	Large scale not specific area	2025	[42]

Abbreviations: LST (Land Surface Temperature), TIRS (Thermal Infrared Sensor), UHI (Urban Heat Island), ETM (Enhanced Thematic Mapper), NDVI (Normalized Difference Vegetation Index), RTE (Radiative Transfer Equation), SWA (Split-Window Algorithm), SCA (Single-Channel Algorithm), MWA (Mono-Window Algorithm), MODIS (Moderate Resolution Imaging Spectroradiometer), SAVI (Soil-Adjusted Vegetation Index), fc (Fractional Vegetation Cover), TIR (Thermal Infrared), UAV (Unmanned Aerial Vehicle), GCPs (Ground Control Points), GIS (Geographic Information System), LCZs (Local Climatic Zones), UTFVI (Urban Thermal Field Variance Index), HRTF (High-Resolution Thermal Fusion), ML (Machine Learning).

The vibrant fabric of Riyadh's culture is a testament to the city's Bedouin traditions, Islamic heritage, and the swift modernization of Saudi society. Thus, Dhahran, a city in the Eastern Province of Saudi Arabia, has a rich history as the site of the first commercial oil discovery in the Kingdom, marking its significance in the global oil industry. The city experiences a hot desert climate, with temperatures soaring above 40°C in summers and mild winters. Geographically, Dhahran is strategically 26°16′N 50°09′E, near the coast of the Persian Gulf, forming part of the Dammam Metropolitan Area1. The Population of Dhahran is increases [46]. Thus, the trend line indicated an increase in the temperature of 0.05°C per year [47]. Tourists in Dhahran can explore the King Abdulaziz Center for World Culture, also known as Ithra, which is a beacon of art, culture, and knowledge [48]. While not known for traditional archaeological sites, the city's culture is deeply intertwined with the oil industry and modern development. The cultural landscape of Dhahran is characterized by a blend of traditional Saudi customs and a cosmopolitan lifestyle influenced by its expatriate communities and educational institutions like the King Fahd University of Petroleum and Minerals (KFUPM) [49]. Abha is positioned at the geographic coordinates 18°, 13′, 1″ N and 42°, 30′, 19″, E, is a region famous for its attractive scenery encompassing mountains, valleys, and verdant plains. Because of its high altitude (2270 meters above mean sea level), this area has a year-round mild environment with moderate summer temperatures and abundant rain. As a result, it attracts a sizable number of travelers seeking safety from the extreme weather. This region

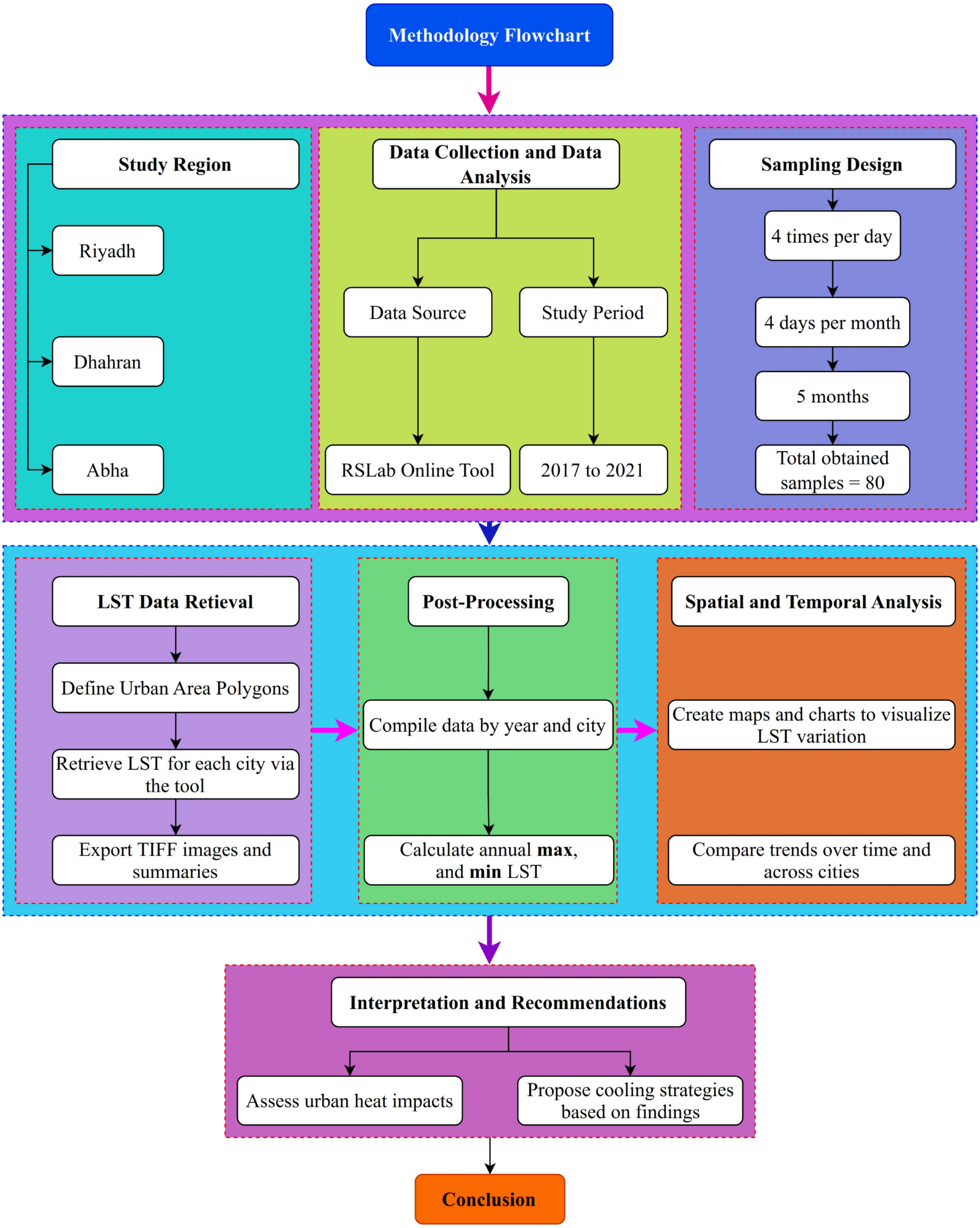

Fig. 1. Adopted methodological framework for this study.

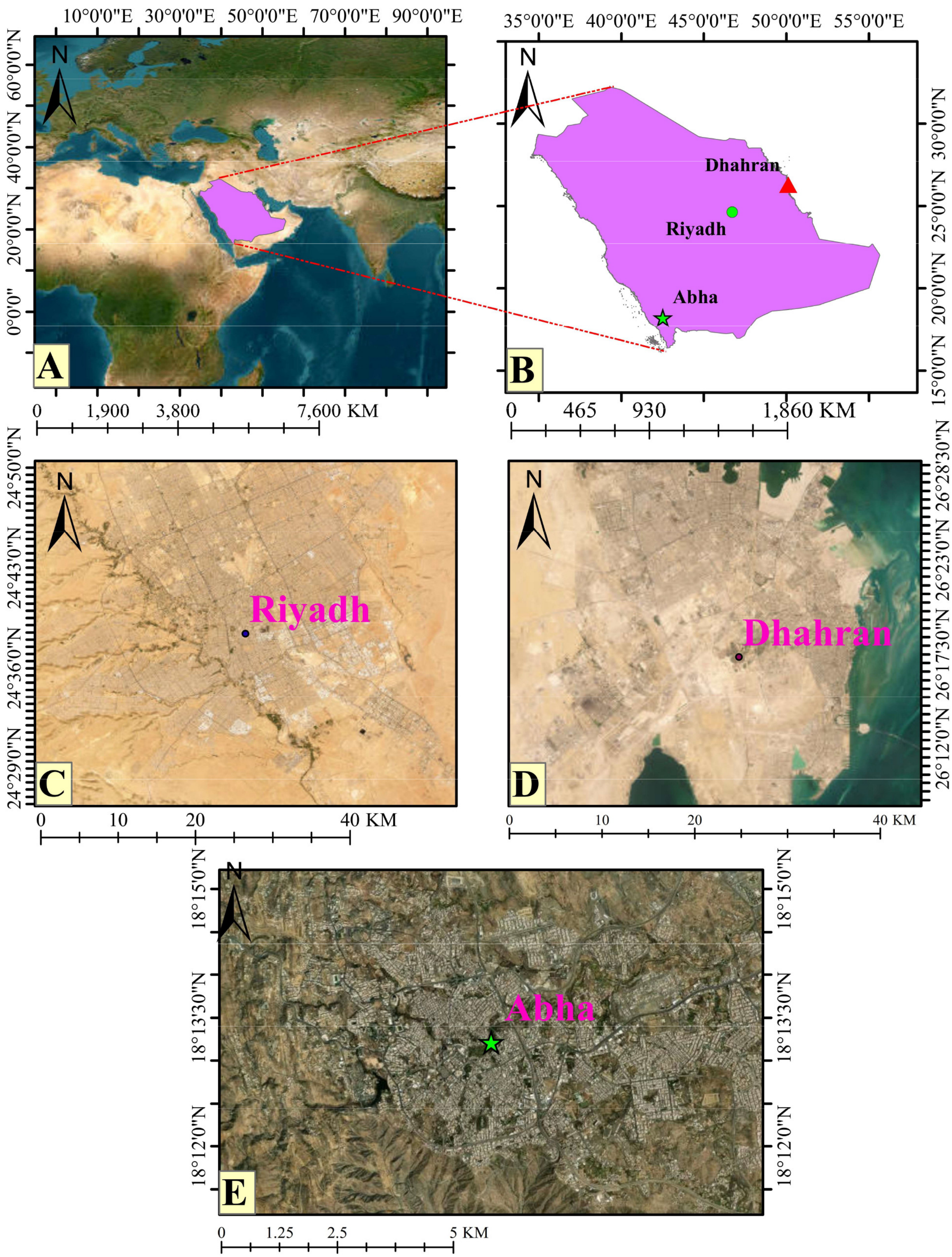

Fig. 2. Study Region Maps; (A) KSA location on world map, (B) KSA map, (C) Riyadh city, (D) Dhahran City, (E) Abha city.

is a homebased to several ancient monuments, including the well-known Shada palace, which was built around 1927 AD and is now a museum showing historical artifacts [50]. The Al Miftaha art village is the place to view the works of local artisans and artists displayed with cultural performances. Abha is made more charming by the more than 300-year-old ancient stone and mud homes, which have a characteristic construction made to survive the heavy rains. around history, watchtowers made of stone have been carefully placed around the landscape to ward off potential invaders [51].

2.3. Data collection and analysis

This study compiled Land Surface Temperature (LST) data entirely using the RS Lab Landsat LST web-based tool developed by the Remote Sensing Lab (RSLab) at the Foundation for Research and Technology – Hellas (FORTH) [9, 52]. The tool provides a user-friendly interface, allowing users to retrieve LST data globally from Landsat thermal imagery paired with surface emissivity products such as MODIS. By using this platform, this study did not find the need for raw data preprocessing, atmospheric correction, and algorithmic calibration, as the tool itself integrated these capabilities with high reliability and scientific validity.

LST data were compiled for three major Saudi Arabian cities encompassing Riyadh, Dhahran, and Abha which representing different climatic zones. The temporal range spans 2017 to 2021, and the analysis was focused on the summer months from May to September, which represent the peak thermal period in the region. All data retrievals were carried out directly through the RS Lab tool, which enables users to define polygons of interest, specify time ranges, and select thermal bands along with emissivity sources. For Riyadh city, LST values were retrieved for four specific days per month, with temperature readings sampled at four different times per day to capture diurnal variation. In Dhahran and Abha cities, a similar retrieval structure was applied, emphasizing seasonal and climatic variability between coastal humid, high-altitude, and arid desert environments. Although the underlying thermal imagery was sourced from Landsat 8's TIRS (Thermal Infrared Sensor), surface emissivity values were derived from the MODIS emissivity product to ensure better accuracy and consistency. A recent review on SWAT-based hydrological modeling has emphasized that the resolution of input data, such as DEM, LULC, and climatic variables critically affects model accuracy and output reliability, a finding that resonates with the current study's emphasis on data quality in environmental modeling [53]. This combination is fully supported by the RSLab LST tool, which offers flexible emissivity input options and facilitates reliable temperature estimation.

All spatial queries, date filters, and data outputs—including TIFF images and statistical summaries—were generated using the RSLab tool interface at https://rslab.gr/Landsat_LST.html. This ensured methodological consistency across all sites and minimized user-driven processing errors. The retrieved data were then post-processed for visualization, statistical comparison, and spatial interpretation. The use of this platform not only enhanced the reproducibility of the study but also reduced the computational and technical burden typically associated with LST extraction from satellite imagery. The RSLab Landsat LST application thus served as the exclusive data source for this research, playing a central role in the study's methodology. A summary of the data acquisition scheme is presented in Table 2, including temporal distribution, observation frequency, and source attribution.

2.4. Data retrieval framework: RS lab landsat LST tool

In this study, all LST data were compiled using the Landsat LST web application developed by the Remote Sensing Lab (RSLab) at the Foundation for Research and Technology – Hellas (FORTH), available at https://rslab.gr/Landsat_LST.html. This web-based application is built on the Google Earth Engine platform and provides on-demand global LST products derived from Landsat 5, 7, and 8 thermal imagery. The application internally applied the Single Channel (SC) algorithm for LST retrieval, which estimates

Table 2. Summary of data.

	Climatic Condition					
Location	Years	Months	Date	Time	Source title	Reference
Riyadh Dhahran Abha	2017–2021	May Jun July August September	Four different days for every month	Four different times in a day	Landsat Land Surface Temperature	[52]

surface temperature based on radiance measured in a single thermal band. To correct for atmospheric effects, the application incorporated the Jiménez-Muñoz parameterization, which used coefficient tables generated from MODTRAN simulations to estimate atmospheric transmissivity, path radiance, and downwelling irradiance. This approach eliminated the need for user-side atmospheric correction or calibration. The tool supports three options for surface emissivity input: (i) MODIS-derived emissivity (daily 1 km product), (ii) ASTER-based global emissivity map (2000–2008), and (iii) NDVI-based emissivity derived from Landsat surface reflectance. In this study, the MODIS emissivity product was selected to ensure consistency and compatibility with the urban land cover conditions in Saudi Arabia. The RS Lab application has been validated against ASTER LST and alternative Landsat LST products, yielded a root mean square error (RMSE) of approximately 1.5°C. Detailed methodology and validation can be found in [9].

2.5. RS-LST aggregation framework (RSLAF)

This study employed a structured method for compiling and aggregating Land Surface Temperature (LST) data from urban areas using the RS-LST Aggregation Framework (RSLAF). The framework relies on data retrieved from the RS Lab Landsat LST web application, which is based on the Single Channel algorithm and the Jiménez-Muñoz parameterization, implemented through the Google Earth Engine platform [9, 52]. To analyze thermal conditions across Riyadh, Dhahran, and Abha cities, LST data were retrieved for the summer season were defined as the period from May to September, for the years 2017 to 2021. For each city, the user interface of the RSLab tool was used to define an urban-area polygon, select Landsat 8 thermal imagery as the data source, and apply MODIS emissivity (MOD11A1 product) as the surface emissivity input. The sampling design involved selecting four different days per month and retrieving LST at four different time intervals per day, resulting in a total of 80 samples per city, per year, as expressed in the following formula:

$$N = D \times M \times T = 4 \times 5 \times 4 = 80 \tag{1}$$

where D is the number of days per month, M is the number of months, and T is the number of time samples per day. Each LST value retrieved (LST_i) represents a single spatial-temporal observation within the defined urban extent. After compiling all 80 values per year, the annual maximum and minimum LSTs were computed using basic aggregation operations. The maximum LST for a given year y was calculated as:

$$LST_{\max}^{(y)} = \max\left(LST_1, LST_2, \ldots, LST_N\right) \tag{2}$$

Similarly, the minimum LST for each year was calculated as:

$$LST_{\min}^{(y)} = \min\left(LST_1, LST_2, \ldots, LST_N\right) \tag{3}$$

If desired, the mean LST across the sampled period can also be computed to indicate central tendency, using the equation:

$$\overline{LST}^{(y)} = \frac{1}{N}\sum_{i=1}^{N} LST_i \tag{4}$$

In this study, emphasis was placed on reporting the extreme values (maximum and minimum) to characterize the intensity and variability of surface heating in each city. The results are presented in annual comparative charts (refer to results section), allowing for both temporal and spatial comparison of thermal behavior across different climatic zones. By formalizing this approach as RSLAF, the study ensured methodological consistency, reproducibility, and clarity in the derivation of LST indicators from remotely sensed data.

3. Results representation

3.1. Land surface temperature analysis for Riyadh

In 2017, the LST in Riyadh ranged from 33.42°C to 48.09°C (Fig. 3a), indicated substantial thermal variation across the urban landscape. In 2018, both minimum and maximum LST values decreased slightly, ranging from 30.96°C to 41.37°C (Fig. 3b), likely due to short-term meteorological moderation such as increased wind activity or cloud cover. In 2019, the maximum LST rose to 50.24°C (Fig. 3c), while the lower end dropped significantly, suggesting intensified thermal contrasts possibly driven by land cover heterogeneity and patchy vegetation loss. In 2020, the LST range remained wide from 15.69°C to 50.14°C (Fig. 3d), reflecting strong differences between urban cores and surrounding semi-urban areas. By 2021, the maximum LST further increased to 53.20°C (Fig. 3e), indicating escalating urban heat intensity, likely exacerbated by continued expansion of impervious surfaces and declining vegetation. The growing temperature extremes over the five-year period underscored the importance of integrating passive cooling strategies and enhancing vegetative cover to reduce urban heat accumulation and improve energy efficiency.

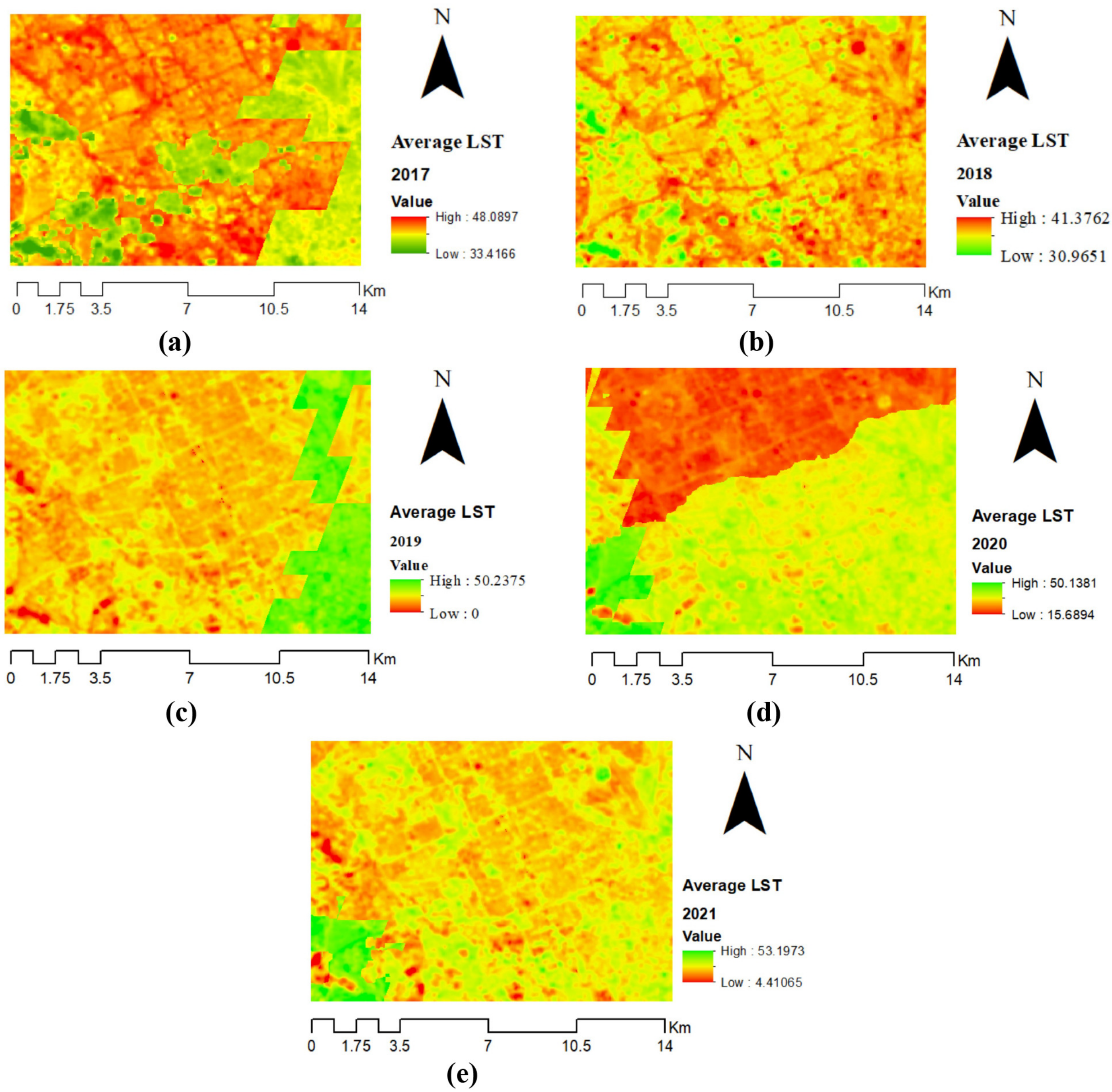

Fig. 3. Average of the LST for urban areas of Riyadh; (a) in the year 2017, (b) in the year 2018, (c) in the year 2019, (d) in the year 2020, and (e) in the year 2021.

Throughout the study period, the urban area of Riyadh exhibited a clear upward trend in maximum LST, increasing from 48.0°C in 2017 to a peak of 53.0°C in 2021, suggesting a progressive intensification of surface heating likely driven by expanding impervious surfaces and reduced vegetation cover. Meanwhile, the minimum LST values fluctuated substantially, dropping from 33.5°C in 2017 to 0.0°C in 2019, and then partially recovering to 15.6°C in 2020 before falling again to 4.4°C in 2021. This pronounced variability in minimum temperatures, coupled with a steady rise in maximum values, indicates a widening diurnal temperature range, which may reflect localized disparities in land cover, material reflectivity, and microclimatic influences across the city. These patterns underscore the intensifying thermal pressure in Riyadh and reinforce the urgency of implementing targeted urban cooling interventions, particularly in high-density zones where temperature extremes are most severe (Fig. 4).

3.2. Land surface temperature analysis for Dhahran

In 2017, the LST ranged from 29.27°C to 54.76°C (Fig. 5a), showed significant thermal contrast between vegetated and built-up areas. In 2018,

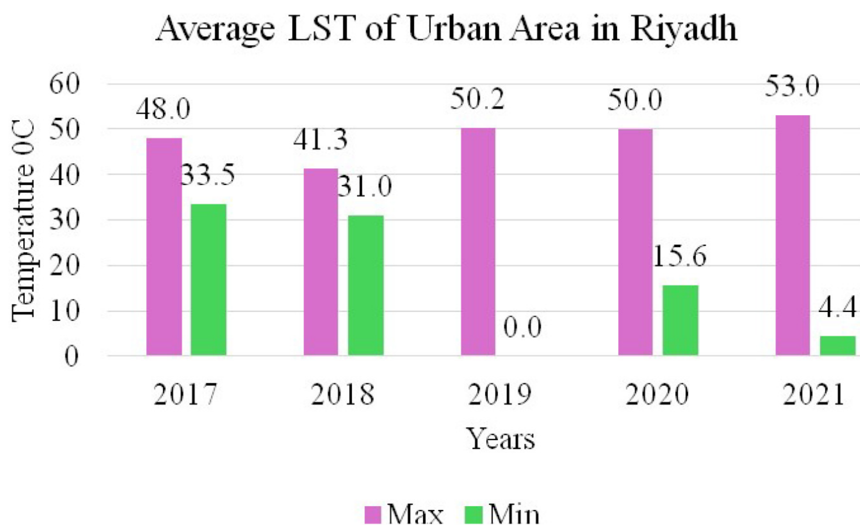

Fig. 4. LST comparison of urban areas of Riyadh 2017–2021.

the minimum LST increased to 36.79°C, while the maximum decreased to 49.93°C (Fig. 5b). This shift suggests a reduction in nighttime cooling and a slight moderation of extreme daytime heating. The elevated minimum LST can be attributed to increased urban surface sealing and heat retention from built-up materials, which reduce nocturnal radiative cooling. Meanwhile, the decrease in maximum LST may be linked to transient atmospheric factors such as higher humidity or cloud cover during peak summer days, which limit solar irradiance at the surface. In 2019, the LST again showed a wide range from 27.48°C to 52.67°C (Fig. 5c), indicating intensified daytime heating likely due to reduced vegetative cover and increased urban expansion. In 2020, the temperature range broadened further from 18.08°C to 59.67°C (Fig. 5d), suggesting stronger radiative cooling at night in peripheral zones and more intense daytime heating in densely urbanized cores. The sharp rise in maximum temperature is indicative of intensified UHI effects, possibly driven by expansion of impervious surfaces and diminished evapotranspiration. By 2021, the minimum LST rose dramatically to 44.73°C, with the maximum reaching 60.64°C (Fig. 5e). This consistent increase in both lower and upper extremes suggests compounding effects of urban densification, continued vegetation loss, and possibly prolonged heatwave events. The persistence of elevated temperatures reflects not only anthropogenic land use changes but also potential regional climate shifts, amplifying the local thermal environment. Therefore, to mitigate extreme LST and reducing energy demand, implementing reflective roofing materials and expanding urban greenery can significantly lower surface heating and improve thermal comfort.

Over the five-year period, Dhahran experienced a marked escalation in maximum LST, rising from 54.7°C in 2017 to 60.6°C in 2021, reflecting an intensifying thermal environment closely linked to expanding urban density and reduced surface albedo. In contrast to Riyadh, the minimum LST values in Dhahran remained relatively higher across all years, ranging from 29.2°C to 44.7°C, with a noticeable increase in baseline temperatures, particularly after 2019. The narrowing gap between maximum and minimum LST suggests sustained heat retention and declining nocturnal cooling, which may be attributed to increased built-up areas, reduced vegetation cover, and limited surface permeability. This consistent upward trend in both daytime and nighttime temperatures underscores the growing severity of urban heat accumulation in Dhahran and highlights the urgent need for climate-adaptive interventions that address both radiative and convective heat processes (Fig. 6).

3.3. Land surface temperature analysis for Al Abha

In 2017, LST in Abha ranged from 9.01°C to 41.46°C (Fig. 7a), reflecting a significant thermal spread likely influenced by elevation gradients and mixed land cover types. In 2018, both minimum and maximum LST values decreased to 3.36°C and 23.23°C (Fig. 7b), respectively, which may be attributed to cooler seasonal conditions or increased vegetation moisture following rainfall events. By 2019, temperatures ranged from 7.05°C to 29.29°C (Fig. 7c), showed a moderate increase compared to the previous year, possibly due to localized reductions in vegetation or development pressures. In 2020, the LST rose sharply, ranging from 19.87°C to 42.20°C (Fig. 7d), indicated

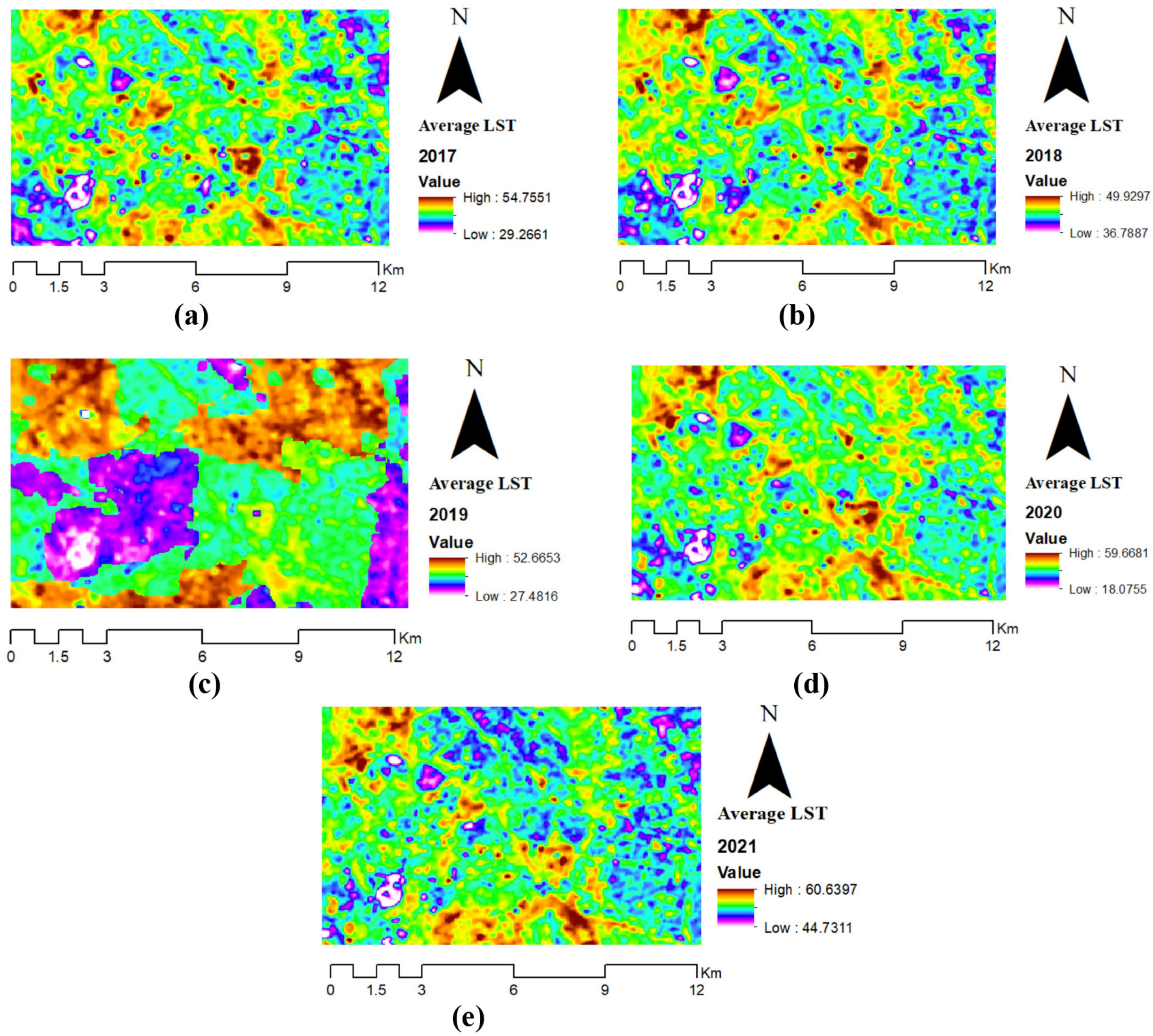

Fig. 5. Average of the LST in urban areas of Dhahran; (a) in the year 2017, (b) in the year 2018, (c) in the year 2019, (d) in the year 2020, and (e) in the year 2021.

unusually high surface heating likely influenced by reduced cloud cover and prolonged dry periods. In 2021, the range narrowed slightly from 9.10°C to 32.96°C (Fig. 7e), suggested more balanced thermal conditions, potentially due to short-term climatic variability or improved vegetation health in certain areas. Despite being a high-altitude city with generally cooler climate, Abha is showing signs of increased surface heating. Targeted urban greening and conservation of vegetated zones can play a crucial role in limiting future temperature rise and preserving thermal comfort.

Comparatively, Abha exhibited a markedly cooler thermal profile compared to Riyadh and Dhahran, consistent with its high-altitude location and dense vegetative cover. Maximum LST values remained relatively stable around 41–42°C between 2017 and 2020, before dropping to 33.0°C in 2021, suggesting a temporary relief in surface heating, possibly due to seasonal climatic variability or improved vegetation health. Minimum LST values showed more fluctuation, rising from 9.0°C in 2017 to a peak of 20.0°C in both 2018 and 2020, then falling again to 9.0°C in 2021. The consistency in upper temperature limits, alongside the variability in minimum values, points to localized climatic moderation and the buffering effect of natural land cover in Abha. These trends confirm that while Abha remains the least heat-stressed among the three cities studied, it is not immune to surface warming, and proactive environmental conservation will be critical to preserving its thermal comfort and ecological stability (Fig. 8).

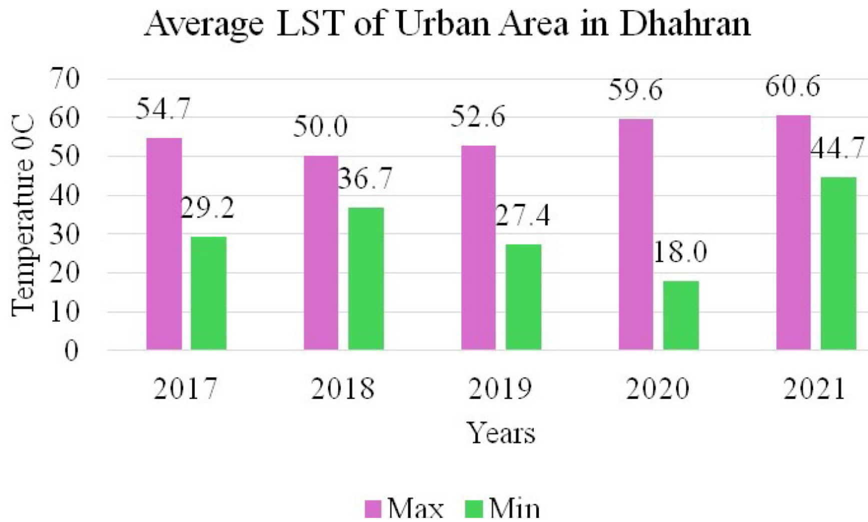

Fig. 6. LST comparison of urban areas of Dhahran 2017–2021.

4. Discussion

Prior studies has repeatedly emphasized the importance of LST research in comprehending urban heat dynamics and directing climate-responsive urban planning. Recent similar research [54] in arid and semi-arid locations have indicated a substantial association between urbanization, plant loss, and rising surface temperatures, particularly in high-density metropolitan areas such as Riyadh and Dhahran. However, most previous studies have concentrated on climatic zones or short-term LST patterns, limiting their application in nations such as Saudi Arabia, which have different topographies and meteorological conditions. Furthermore, few studies explored the effects of LST fluctuation on actual urban engineering aspects, such as infrastructure materials, building orientation, or cooling requirements. These LST values were calculated using the Single Channel and Jimenez-Munoz retrieval models, which enabled for precise surface temperature estimation across a wide range of land cover and meteorological conditions. The integration of both models produced strong thermal profiles for each city, validating the dependability of the observed spatial patterns and supporting engineering-level thermal planning. This study investigated thermal data from three climatically diverse Saudi cities Riyadh, Dhahran, and Abha for five years (2017–2021) to evaluate regional LST dynamics and the UHI effect using high-resolution remote sensing. This study had taken the daily data as well in contrast to the published study [55]. Thus, discovered that maximum LST values in Riyadh and Dhahran consistently exceeded 53°C in heavily populated regions, whereas Abha maintained much cooler temperatures below 42.2°C, owing to its high elevation and natural vegetation. The investigation also revealed a growing thermal gap between the dense urban core and the surrounding transitional zones, particularly in Dhahran, indicating the impact of surface composition and urban development on heat buildup. These findings are built on those of [56], and [57], strengthening the idea that urban geometry, plant cover, and land use patterns are important determinants of surface temperature. Our findings highlighted the need to include reflective materials, passive cooling techniques, and green infrastructure into urban planning, particularly in hot desert areas experiencing fast development. Recent hydrological modeling in arid cities such as Herat, Afghanistan, has also emphasized the urgency of integrating climate-resilient infrastructure planning with environmental data analytics, reinforcing the broader relevance of spatial climate indicators like LST in guiding sustainable urban strategies [58]. Our findings demonstrated that thermal disparities persisted beyond seasonal transitions, implying that LST anomalies are more strongly related to urban morphology and land cover than to transient climatic fluctuations. This confirms prior arguments that land use planning must be central to climate adaptation measures. These findings are especially important for urban engineers, architects, and legislators because they show that surface temperature data might be utilized to improve zoning rules, material selection, Heating, Ventilation, and Air Conditioning (HVAC) system planning, and landscape design in arid regions, reducing UHI effects. To our knowledge, this is the first study in Saudi Arabia that provided a multi-regional, multi-year assessment of LST

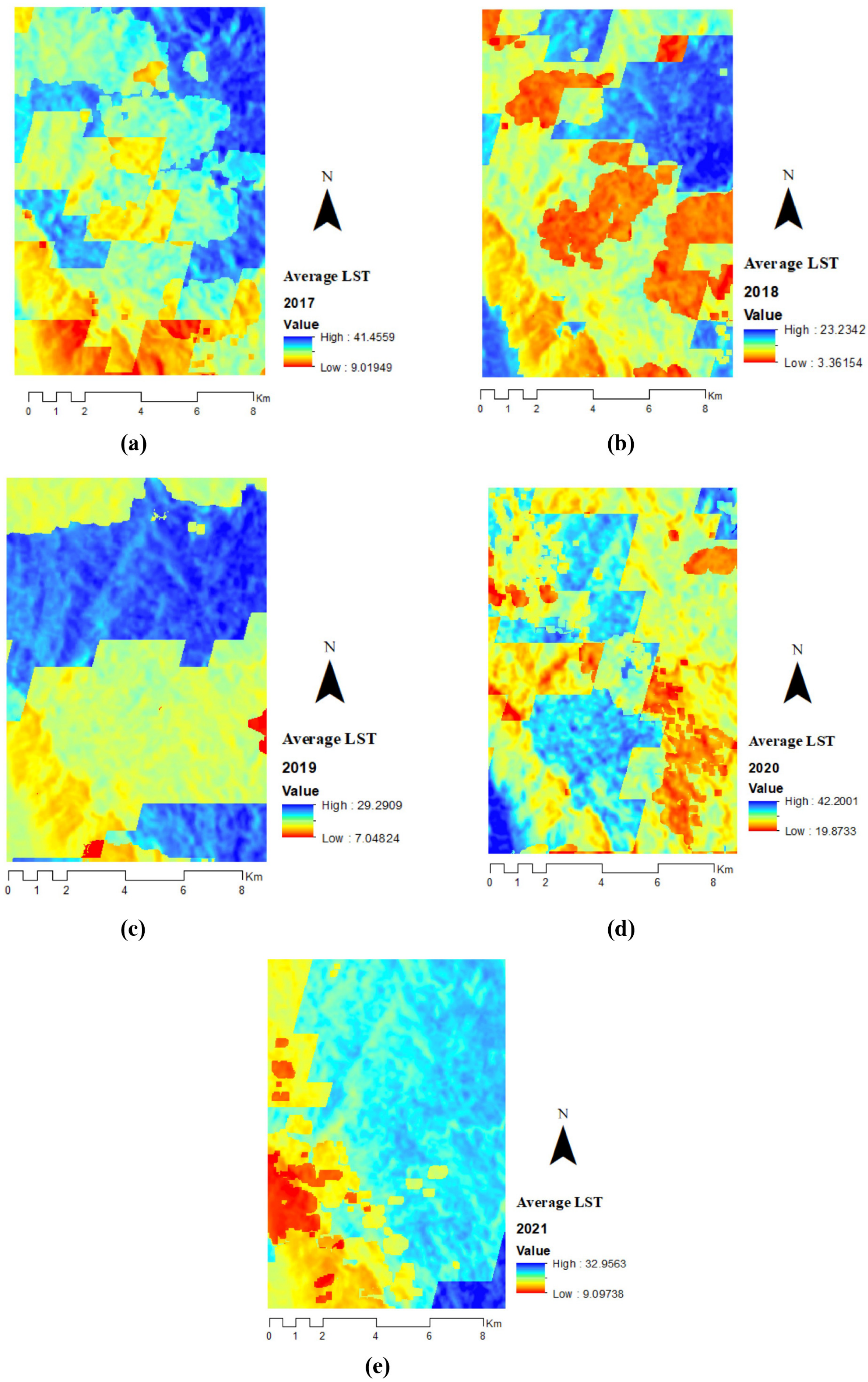

Fig. 7. Average of the LST for urban areas of Abha; (a) in the year 2017, (b) in the year 2018, (c) in the year 2019, (d) in the year 2020, and (e) in the year 2021.

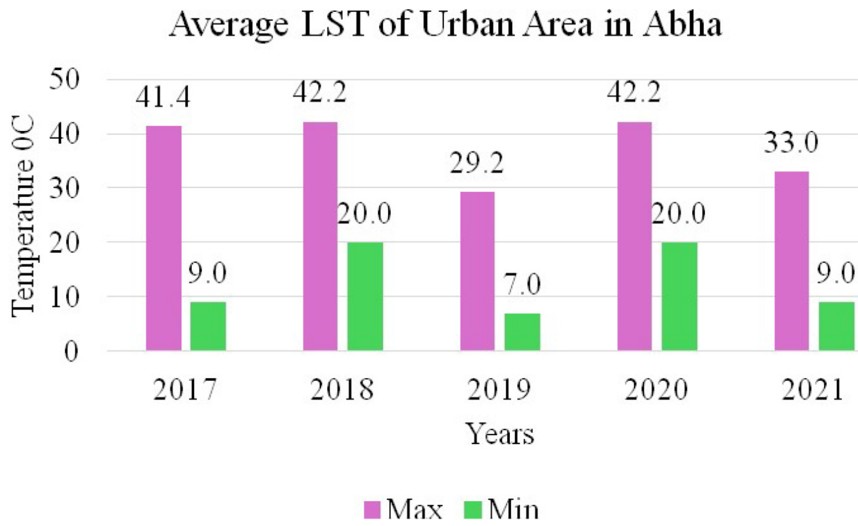

Fig. 8. LST comparison of urban areas of Abha 2017–2021.

trends utilizing Landsat 8 and MODIS data coupled with advanced retrieval models such as the Single Channel and Jimenez-Munoz methods from RSLab [52]. These findings provided strong evidence that spatially resolved LST data can aid in long-term planning for sustainable and thermally comfortable urban environments, particularly when customized to the climatic context of each city. However, certain limits should be acknowledged. The study relied only on satellite-derived data, with no in-situ ground validation, which may have influenced the precision of temperature values in specific terrain types.

5. Conclusion

This study analyzed LST in Riyadh, Dhahran, and Abha from 2017 to 2021 and found that rising temperatures in Riyadh and Dhahran are linked to urban growth, loss of green spaces, and the use of heat-retaining materials, while Abha remained cooler due to its elevation and natural vegetation. Riyadh's maximum temperature reached 53.2°C and its minimum dropped to 0.0°C, showing wide daily variations, while Dhahran showed the highest thermal stress with a peak of 60.6°C and a steady rise in minimum temperatures to 44.7°C, meaning it retains heat even at night. Abha's temperatures stayed between 7.0°C and 42.2°C, reflected its more balanced climate. The results highlighted the clear impact of city design and climate on surface temperatures. Based on these findings, cities should increase green areas, use reflective or cooler building materials, and plan with climate in mind to reduce heat stress. Future studies may add ground-based temperature checks and explore real-time tools to help city planners respond quickly to heat risks.

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