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Research Article

Surface Urban Heat Island (SUHI) Pattern and Trends in main cities of Pakistan: Lahore and Faisalabad

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Abstract

This study analyses the Surface Urban Heat Island (SUHI) patterns and trends in two major cities of Pakistan, Lahore, and Faisalabad, mainly by analyzing their spatial and temporal variations using remote sensing data. The objectives of this study are twofold: first, to comprehensively analyze SUHI dynamics over time and in different urban areas in Lahore and Faisalabad, and second, to investigate the complex relationship between Land Surface Temperature (LST) and Land Use/Land Cover (LULC) in these urban environments. The purpose of this study is to investigate the evolving thermal characteristics of these cities and their relationship with land use and land cover changes by using advanced remote sensing techniques and spatial analysis tools. The results of this study not only contribute to a deeper understanding of urban climate change in Pakistan but also provide valuable insights for urban planners and policymakers in their efforts to reduce the adverse effects of urban heat islands on the quality of life and environmental sustainability in these cities.

Introduction

Background

The surface urban heat island (SUHI) refers to the higher temperatures in urban areas compared to nearby rural areas, caused by human activities and urbanization. The term "urban heat island", which has been known since the 19th century, was formally coined in the 1950s when systematic studies began. SUHI significantly affects urban design, climate adaptation, and public health. The SUHI effect varies during the day and night and is more pronounced at night, known as the nocturnal heat island effect. Daytime heat islands also occur but are influenced by factors such as urban heat output and atmospheric conditions [1]. The magnitude of SUHI depends on factors such as city size, population density, building materials, and green space, with larger and denser cities being more affected. Meteorological conditions, such as heat waves, can exacerbate this effect and amplify the effects of high heat on urban residents [2]. The SUHI effect is driven by urbanization and land use changes, where natural surfaces are replaced with heat-absorbing, impermeable materials. Tall buildings create urban valleys that trap heat and reduce ventilation and night-time cooling. Human activities such as industrial processes, transportation, and heating also release excess heat, amplifying SUHI. The lack of green space in urban areas limits cooling through shade and evapotranspiration provided by vegetation. In addition, dark-colored surfaces in cities absorb more sunlight, increasing temperatures. Understanding the history and trends of SUHI is essential for developing urban planning and climate adaptation strategies, making cities more sustainable and livable. Reducing SUHI helps reduce its impact on public health, energy demand, and urban climate.

An Overview of the SHUI

The surface urban heat island (SUHI) effect refers to higher temperatures in urban areas compared to rural environments, caused by human activities and urbanization. Researchers study patterns and trends of SUHI to address its impacts on urban planning, public health, and climate change adaptation [3]. Found that SUHI is more pronounced at night, leading to warmer nighttime temperatures in cities, and worsens with increasing urbanization and sprawl. Similarly [4], identified a strong positive correlation between city size, density, and the intensity of the SUHI effect [3]. Emphasized that urbanization and land use changes significantly affect SUHI. The replacement of natural surfaces with impermeable materials such as concrete and asphalt reduces the cooling effect of vegetation and soil, leading to an increase in urban temperatures. Human heat is a key contributor to SUHI. Highlighted the role of human activities such as industrial processes, transportation, and energy use in releasing excess heat [3], found that tall buildings and dense urban structures create urban valleys, trapping heat and restricting airflow, increasing temperatures. Studies such as [5], identified the lack of green spaces and vegetation as a key factor in SUHI, as it reduces shade and evapotranspiration, leading to higher urban temperatures. With global temperatures rising, concerns about the impacts of SUHI on public health, energy consumption, and urban planning have increased [6]. Emphasize the need for sustainable urban design and climate adaptation strategies to address these challenges.

Pakistan Scenario

The surface urban heat island (SUHI) effect is widespread in urban areas around the world, including Pakistan. Pakistan, with its rapidly growing urban areas and population, faces significant SUHI challenges. This study examines the patterns and trends of SUHI in Pakistan, focusing on their impact on urban planning, public health, and environmental sustainability.

SUHI Patterns in Pakistan: In urban areas of Pakistan, the SUHI effect is characterized by significant temperature differences between day and night. Cities with heat-absorbing surfaces such as concrete and asphalt are warmer than rural areas, especially during the day. However, the SUHI effect is more pronounced at night, leading to warmer nighttime temperatures in cities such as Karachi, Lahore, Islamabad, and Faisalabad. The extent of the effect varies with the size of the city, building density, distribution of green space, and local climate. Urban sprawl and expansion worsen the SUHI effect, while the urban valley effect caused by tall buildings and dense structures traps heat and reduces ventilation, exacerbating this effect.

SUHI Trends in Pakistan: Over the past few decades, Pakistan has undergone tremendous urbanization and population growth, which has increased the impact of SUHI. As cities grow and industrialization increases, more natural surfaces such as pavement and open ground are being replaced by impermeable materials such as concrete and asphalt. This transition reduces the cooling capacity of the environment and contributes to higher temperatures in urban areas. The relationship between urbanization and the magnitude of the heat island effect is one of the important patterns in SUHI. The reduction of green space in cities, coupled with the increase in heat-absorbing materials, leads to sharp temperature differences between urban and rural locations [7]. Conducted a study in Lahore, Pakistan, which showed that there is a positive relationship between urbanization and SUHI between the extent of built-up areas and the intensity of the heat island effect. Climate change also affects SUHI trends in Pakistan. As global temperatures rise, the heat island effect will intensify, resulting in higher temperatures in urban areas. Research conducted by [8], shows the link between climate change and SUHI, indicating that if climate change is not controlled, urban heat island effects could worsen in the coming decades.

SUHI Scenario in Lahore and Faisalabad: Patterns and Trends

Surface Urban Heat Island (SUHI) is a widespread phenomenon observed in cities around the world, including Lahore and Faisalabad in Pakistan. It refers to the temperature difference between urban and rural areas, with cities experiencing higher temperatures due to human activities and land use changes. Rapid urbanization and industrialization in Lahore and Faisalabad have exacerbated the SUHI effect in these urban areas.

1. **SUHI Patterns in Lahore and Faisalabad:** Lahore and Faisalabad exhibit distinct SUHI patterns during the day and night. During the day, the prevalence of heat-absorbing materials such as concrete and asphalt makes cities warmer than rural areas. For example, on a hot summer day, temperatures in Lahore can be several degrees Celsius higher than in surrounding rural areas. Similarly, at night, Faisalabad's built environment retains heat, causing the city to have higher temperatures compared to its neighboring rural areas.
2. **SUHI Trends in Lahore and Faisalabad:** Lahore and Faisalabad have witnessed significant urban and industrial growth, which has exacerbated the SUHI effect. Replacing green spaces with impermeable materials such as concrete and asphalt reduces cooling and increases temperatures. A study by [7], in Lahore found a positive correlation between the size of built-up areas and the severity of the SUHI effect, with urbanization worsening the heat island effect. Similarly [9], in Faisalabad highlighted how urbanization and the thermal properties of building materials significantly contribute to the increase in city temperatures.

Statement of a problem

a. The difference between day and night temperatures between urban and rural areas in Lahore and Faisalabad will be analyzed to study the SUHI trend. Daytime patterns are influenced by urbanization and heat-absorbing materials, while nighttime patterns are influenced by heat retention in residential areas. This reveals the strength and scope of the SUHI effect in these cities and provides insights into urban planning and climate adaptation under different climatic and seasonal conditions.
b. The second aspect of the study examines historical trends in SUHI in Lahore and Faisalabad, focusing on the impact of urbanization and industrial growth. By analyzing temperature data and land use changes, it aims to link built-up areas with SUHI intensity. Identifying temporal trends highlights the long-term effects of urban growth on regional climate patterns and helps develop sustainable urban planning strategies to mitigate SUHI and improve urban resilience.

The objective of the Study

i. To analyze the spatial and temporal patterns of SUHI in Lahore and Faisalabad using remote sensing data.
ii. To examine the relationship between land surface temperature (LST) and land use/land cover (LULC) in both cities.

Significance of study

a. **Urban Planning:** By combining green infrastructure and efficient land-use strategies, urban planners and policymakers can create sustainable and climate-resilient cities with a deeper understanding of the impact of SUHI.
b. **Public health:** Rising temperatures in urban areas, especially during heat waves, can harm health. Understanding SUHI will help implement measures to protect vulnerable populations and improve urban life.

Environmental Sustainability: The SUHI effect has an impact on biodiversity and local ecosystems. It is possible to create mitigation plans to safeguard natural ecosystems and lessen the negative effects of urbanization on the environment.

Literature Review

[10], investigated the diurnal and seasonal variations in the intensity of the surface urban heat island (SUHII) in 419 global cities and analyzed the temperature difference between urban and suburban areas using MODIS data. They found that the annual mean SUHII during the day (1.5°C) was higher than the SUHII at night (1.1°C), but no correlation was observed between day and night SUHIIs, suggesting different driving mechanisms. Daytime SUHII was negatively correlated with differences in vegetation cover, while nighttime SUHII was positively correlated with differences in light and nighttime light. Their findings emphasize the role of vegetation in reducing daytime

SUHII and suggest that increasing urban vegetation can reduce the urban heat island effect [11], investigated the impact of land use/cover (LULC), and population change on UHI patterns in Shanghai between 1997 and 2008 using remote sensing, GIS, and population data. The study found significant urban growth with a 219.50% increase in developed land, most of which was due to the conversion of agricultural areas and vegetation. This led to significant fluctuations in UHI intensity. The study highlights the need to consider land conversion patterns and urban climate responses when analyzing environmental impacts during urban planning. [1], studied the intensity of the urban heat island (UHI) in 32 major cities in China from 2003 to 2011 using MODIS data. They found significant geographical variation in daily and seasonal surface UHI intensity, with higher SUHII values in the southeastern and northern regions. SUHII during the day was related to vegetation, anthropogenic heating, and climate, while SUHII at night was influenced by albedo, construction intensity, and climate. Their findings highlighted the complex mechanisms behind SUHII variations, especially during summer, and emphasized the need for different strategies to mitigate the UHI effect [12], mapped the UHI effect across Sydney using MODIS and Landsat data from 2003 to 2015. The study found that daily UHI intensity in Sydney can reach 7-8°C in July, with milder intensities at night. While the overall daily UHI trend showed a slight increase, significant intensification occurred during the day in dense urban areas. Landsat-8 data provide more detailed information on urban hot spots, demonstrating the usefulness of satellite data in monitoring and mapping UHI trends over time and space.

[5], investigated the temporal trends of SUHI in 31 major cities in China from 2001 to 2015 using MODIS LST data and the China Land Use/Cover Dataset (CLUD). They analyzed the SUHI intensity (SUHII), SUHI area, and percentage of SUHII growing area (PAISUHII). The study found that the SUHII area and SUHI increased significantly during summer days but decreased in many cities during summer and winter nights. Correlation analysis showed that SUHII was negatively correlated with background LST in urban areas, especially in northern China. Vegetation loss and increased anthropogenic heat emission were key factors in the increase of SUHII [6], introduced a new method to quantify surface UHI intensity (SUHII) by linking MODIS LST with impervious surface areas (ISA) using kernel density estimation (KDE). This method regionalized ISA to improve the LST-ISA relationship. The study showed that SUHII, defined by the slope of the LST functions, was higher in summer and during the day compared to winter and at night. This approach was validated using Landsat data, demonstrating its reliability for assessing urban heat island effects [13], studied the spatial, diurnal, and seasonal fluctuations of surface UHI intensity (SUHII) in 31 cities in China from 2001 to 2015. A significant increase in SUHII was observed during summer and winter days and nights, with 71.0%, 58.1%, 25. %, and 54.8% of cities showing an increase in SUHII during these periods, respectively. Correlation analysis showed that daytime SUHII was negatively correlated with background LST and mean air temperature, while nighttime SUHII was associated with precipitation and sunshine duration. Factors contributing to the increase in SUHII include vegetation loss and population growth, with vegetation loss leading to larger SUHII increases in cities.

[14], proposed a new technique to analyze spatial and temporal fluctuations in SUHII using Shannon entropy and Pearson chi-square statistics. This study combined Landsat imagery, MODIS data, and meteorological information from 1985 to 2017 for Babol, Iran. SUHII was calculated using LST maps and the SUHI ratio index. The study showed a 24% increase in SUHII over time and a strong correlation between air temperature differences and SUHII values with a coefficient of 0.82. The research highlighted the significant impact of SUHII on vegetation, air quality, energy consumption, human health, and climate change [15], conducted an extensive review of satellite-based SUHI research from 1972 to the present and noted a significant shift in focus since 2005. Research has mainly focused on China and summer days, with about two-thirds of studies examining regional differences in SUHI/LST. Landsat TM/ETM+/TIRS and MODIS are the most commonly used satellite sensors, accounting for 78% of the studies. The review highlighted key findings, methodologies, and challenges, and emphasized limitations in data and methods. Future research should focus on unexplored areas, refining the assessment of SUHI power, and integrating in situ observations and numerical models [7], examined the relationship between surface urban heat island (SUHI) and temperature changes in urban areas. They found that maximum temperatures were recorded in residential and barren areas, while cooler temperatures were observed in vegetated areas. In Lahore, surface temperatures have increased by 2°C over the past two years, while Faisalabad and Multan have seen increases of 2°C and 4°C respectively over the past 19 years.

[16], tracked the SUHI trends in the Changsha-Zhuzhou-Xiangtan (CZT) region from 2000 to 2017 using Landsat time series data and Google Earth Engine. Analytical methods such as Mann-Kendall test, Theil Sen median trend analysis, and standard deviation ellipse were applied. It was found that SUHI is more prevalent in summer, and Zhuzhou shows higher intensity compared to Changsha and Xiangtan. The study attributed the regional variances in SUHI patterns to land cover changes, including the shift towards impervious surfaces and the influence of active factories [17], calculated the surface urban heat island intensity for 36 major cities in China from 2001 to 2017 using MODIS images and two methods: the administrative boundary (AB) technique and the optimized simple urban method (OSUE). This study examined the spatiotemporal disparities in SUHI patterns at regional and national levels and examined the relationship between urban development and SUHI intensity [7], examined UHI in urban areas and found that urban surface temperatures were generally higher than rural areas. Using Landsat TM/OLI data from 1998 and 2017, the study mapped land use and cover patterns and showed that built-up and dry areas had the highest temperatures, while vegetated areas were cooler. The study found that surface temperatures in Lahore, Faisalabad and Multan have increased by 2°C, 2.2°C and 2.4°C, respectively, over the past 20 years. The findings highlighted a positive correlation between LST, built-up areas and vegetation loss, underscoring the need for effective urban planning to manage urbanization and mitigate the impacts of UHI.

[18], studied the impact of urbanization on climate change, focusing on the UHI effect in the Beijing-Tianjin-Hebei (BTH) region. They found that the intensity of UHI was highest in central areas with temperatures decreasing towards the suburbs. Beijing's rapid urban expansion resulted in the most severe SUHI. The study concluded that larger urban scales and dense populations exacerbate the effects of UHI and provided design recommendations to reduce UHI and enhance urban climate resilience [19], studied the UHI effect in Ahmedabad and Gandhinagar, India, using Landsat 8 LST data for day and night. They found strong correlations between LST and land cover indices, with R2 values of 0.63 (Ahmedabad) and 0.79 (Gandhinagar) during the day, and higher correlations at night. The models in this study, tested with MODIS data across seasons, show good applicability to semi-arid urban areas and potential for broader temporal analyses [20], calculated the intensity of the surface urban heat island (SUHII) over the Kowloon Peninsula and Hong Kong Island using radiometric and surface temperature data. Analyzing Landsat TM and ASTER imagery, along with high-resolution thermal data from aircraft, they found that urban geometry significantly affects SUHII, with structural

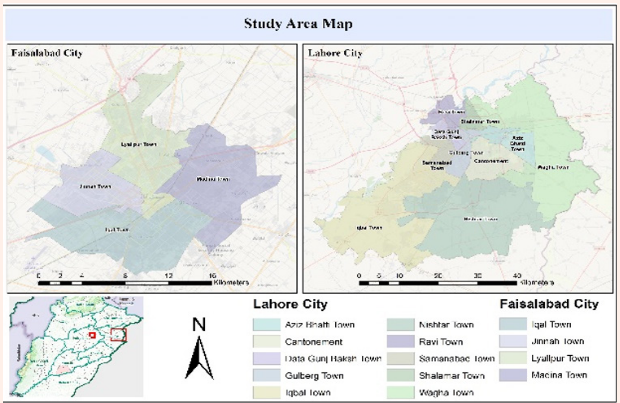
features exacerbating the UHI effect when using corrected temperatures (SUHIIc) compared to radiometric temperatures (SUHIIr) [21], analyzed the surface urban heat island (SUHI) in 16 cities in the Yangtze River Delta using MODIS LST data. They found that anthropogenic factors were the primary drivers of SUHI, and that environmental variables such as vegetation cover and proximity to water were also important. Using a boosted regression tree model, they assessed factors such as distance from buildings, roads, and water, and highlighted spatial variations in SUHI related to social and economic inequalities [22], analyzed long-term thermal trends in Lucknow, Kolkata and Pune using MODIS data. They found a reduction in diurnal temperature range (DTR) due to an increase in night-time LST and observed urban cooling in Pune, likely due to increased particulate matter and vegetation cover. The warming was more pronounced during monsoon and summer nights, while the SUHII trend was different – it increased in Kolkata and Pune but decreased in Lucknow. This study highlights the influence of geographical and climatic factors on urban heat dynamics.

[8], analyzed the trend of surface urban heat island (SUHI) in Wuhan and Nanchang (1984–2018) using Landsat data. Nanchang showed higher and more variable SUHII with increasing urban LST, while Wuhan's SUHI initially increased before decreasing. Despite different temporal trends, spatial patterns remained consistent across SUHII definitions. This study highlights the dynamics of evolving SUHI in both cities [9], analyzed environmental changes in Pakistan during the COVID-19 lockdown and revealed a reduction in energy consumption (1786 GWh) and a significant reduction in air pollution. Satellite data showed a 40% reduction in NO2 from coal plants, a 30% reduction in urban areas, and a 25% reduction in AOD in industrial areas. Transportation restrictions also reduced the urban heat island effect. This study highlights the importance of satellite data for monitoring pollution and air quality [2], examined the role of green infrastructure in mitigating the urban heat island (UHI) effects through case studies of 14 cities in 13 countries. The study found that the intensity of UHI varies based on urban morphology and microclimate, while green spaces can help mitigate heat effects. It also emphasized the link between UHIs, heat waves, and climate change, highlighting the benefits of expanding urban green spaces [21], analyzed the effects of the urban heat island (UHI) in Hangzhou, China, using Landsat thermal data. The study found that the intensity of the SUHI shifted northward (1990–2010) and southward (2010–2018), which is consistent with urban expansion. The growth of infill in the city center and the reduction of green infrastructure worsened the SUHI. The findings highlight the need for sustainable urban planning to mitigate heat impacts and enhance livability.

[23], investigated surface urban heat islands (SUHI) in the Yangtze River Delta using MODIS LST data for 16 cities. Using stratified random sampling (78,085 points) and a boosted regression tree model, they identified urbanization as the primary driver of SUHI, alongside natural factors. Socioeconomic changes affected the severity of SUHI, and urban growth played a major role. This study provides a new method to assess the effects of land use on SUHI [24], analyzed land use/cover change (LULC) and urban heat in Karachi (2000-2020) using Landsat data. The built-up area increased from 97.6 km2 to 325.33 km2, with an increase in land surface temperature (LST) due to loss of vegetation cover. Statistical analysis revealed a strong association between LST and urbanization, with high-density vegetation cover helping to regulate heat. This study highlights the need for adaptive land use planning to mitigate the urban heat island effects.

[25], used MODIS and Landsat data to develop a model to quantify the changes in UHI (SUHI) levels in the Jingjin-Ji region of China (2003–2018). The study found that suburban areas had the largest SUHI fluctuations, with a sharper increase during the day. The seasonal variations were driven by changes in rural vegetation, while urban sprawl caused interannual variations. Urban greening efforts contributed to the reduction of SUHI, especially in summer. These findings enhance the understanding of UHI dynamics and support mitigation strategies [26], introduced a more accurate and efficient method to assess the intensity of the surface urban heat island (SUHI) in China. The study found that 81.02% of Chinese cities, mainly in the south, experience SUHI, which is caused by factors such as humidity, vegetation, evapotranspiration, and industrial activities. This highlights regional variations, warns against standard regression models, and challenges the assumption that larger cities experience higher SUHI intensity, and emphasizes the need for further research in smaller cities [27], analyzed the intensity of the urban heat island (UHI) in Lisbon and Porto (2008-2017) and found a maximum temperature of 3.5 °C, with stronger effects during winter nights. Lisbon had a higher urban heat island effect (1.5 °C reduction) than Porto (1 °C). The UHI was more intense during the summer day and in dense urban areas. Under the RCP8.5 scenario, the UHI is projected to increase by 0.25 °C per year in Lisbon and by 0.3 °C per year in Porto by 2050. These findings highlight the need for sustainable urban planning to mitigate climate impacts.

Figure 1: Study Area map.



Material and Methods

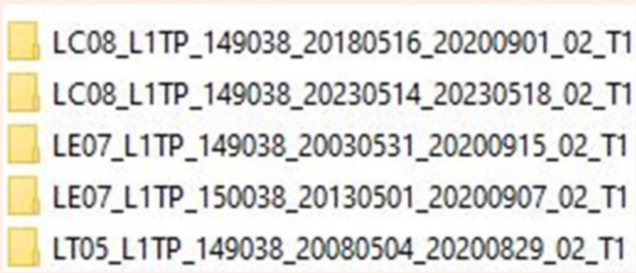
Study Area: Faisalabad is a prominent industrial city and the third most populous metropolis in Pakistan. It is located approximately 225 km south of Islamabad and lies between latitudes 30°35' to 31°47' N and longitudes 72°73' to 73°40' E. It is bordered by Sahiwal District to the east, Sahiwal and Toba Tek Singh Districts to the south, and Jhang District to the west. Faisalabad is connected by the M-3 Highway, which connects it to the Islamabad-Lahore Highway M-2. Historically, the city was developed as a mandi town with an area of 3 km², designed for a population of 20,000. Faisalabad, known as the Manchester of Pakistan, is known for its textile industry.

Lahore, the "Garden City," is located in the northeastern region of Pakistan between latitudes 31°15' to 31°45' north and longitudes 74°01' to 74°39' east. It is bordered by Wagah to the north and west and Kasur District to the south, with the Ravi River flowing along its northern border. Lahore, 60 km west of Amritsar, India, is the second largest city in Pakistan and a historical and cultural hub. It has a semi-arid climate and has played a pivotal role in various historical periods, including the Ghaznavid, Mughal, Sikh, and British periods. Lahore, famous for its historical monuments, cultural diversity, and educational institutions.

Data Sources

To study the Surface Urban Heat Island (SUHI) pattern and trend's in Lahore and Faisalabad various data sources have use. The study have utilize remote sensing data obtained from Landsat 5, Landsat 7 and Landsat 8 satellite. The land surface temperature (LST) and land use land cover (LULC) data extract from Landsat 5, Landsat 7 and Landsat 8 satellite images for Lahore and Faisalabad for the years May 2003, May 2008, May 2013, May 2018, and May 2023. The extracted data have been analyzed using ArcGIS 10.8 to determine the SUHI pattern and trends for both cities.

Figure 2: Satellite Images of Different Years.



Data Analysis

Land surface Temperature: Data analysis for Land surface temperature (LST) use the statistical tools (raster Calculator) in ArcGIS. Raster calculator should be types and search from the search bar of the geoprocessing window. There are the following step's for calculate LST.

Analysis of Landsat 8 Imagery: The formula below should be typed into the calculation bar of the raster calculator. Through the use of remote sensing data, primarily Landsat 8 images, the goal is to determine the land surface temperature. The procedure entails multiple processes that convert the unprocessed data into accurate temperature readings. Here is a description of each action:

Step 1: Radiance Conversion

The satellite imagery's raw digital numbers (DN) are first transformed into radiance values. Energy radiated in a specific wavelength range and direction is measured as radiation. The conversion's formula is as follows:

$$LST = \frac{BT}{1} + \left(\lambda * \frac{BT}{C2}\right) * Ln(E) \qquad L\lambda = ML * QCAL + AL - Oi$$

a. Lλ is the spectral radiance at the top of the atmosphere (TOA) in watts per square meter per steradian per micrometer ($W/(m^2 \cdot sr \cdot \mu m)$).

b. ML is the radiance multiplicative influence for the band.

c. Qcal agrees to the digital number (DN) of the pixel.

d. AL is the radiance preservative factor for the band.

e. Oi is a correction value specific to Band 10, which is 0.29 in this situation

the top of the atmosphere's (TOA) spectral radiation expressed in watts per square meter, steradian, and micrometers (W/(m2srm)).

Step 2: Brightness Temperature conversion

The brightness temperature, or the temperature of a black body radiating the same amount of radiation as the observed surface, is then calculated from the radiance data. This conversion's formula is:

$$BT = \frac{K2}{Ln\left(\frac{K1}{L\lambda} + 1\right)} - 2.73.15$$

The brightness temperature (BT) is expressed in degrees Celsius (°C). K1 and K2 are constants unique to the sensor and spectral band, respectively. L is the spectral radiance of TOA.

Step 3: Determine NDVI

The density and health of the vegetation are gauged by the Normalized Difference Vegetation Index (NDVI). The reflectance data from two spectral bands are used to calculate it. The NDVI formula is

$$NDVI = (NIR - RED)/(NIR + RED)$$

1. NIR: Reflectance in the Near-Infrared band (usually Band 5 for Landsat 8).
2. RED: Reflectance in the Red band (usually Band 4 for Landsat 8).

$$NDVI = float(Band\,5 - Band\,4)/\,float(Band\,5 + Band4)$$

where 5 Band5 and 4 Band4 represent, respectively, the reflectance values from Landsat 8 Bands 5 and 4.

Step 4: Proportion of Vegetation

The term "Proportion of Vegetation" is use in environmental studies and remote sensing to define how much or how much of an area of interest is covered in vegetation. The ratio of the vegetation area to the overall area under consideration is numerically represented.

$$PV = Squar((NDVI - NDVImini)/(NDVI\max - NDVImini))$$

Step 5: Land surface Emissivity

Land surface emissivity is a fundamental concept in remote sensing and thermal infrared analysis. It refers to the ability of a surface to emit thermal radiation, especially in the form of long infrared radiation, which is a type of electromagnetic radiation emitted by objects due to their temperature.

$$E = 0.004 * PV + 0.986$$

Step 6: Land Surface Temperature

Analysis of Landsat 5 and 7 Imagery: There are the following steps necessary for calculating Land Surface Temperature (LST) from Landsat 5 and 7 thermal infrared data.

Procedure: I collected the thermal infrared band data. For Landsat 5 and 7, this is usually Band 6.

Step 1: Conversion DN to Radiance

The "DN to Radiance conversion" procedure is essential in remote sensing analysis, especially when working with Landsat imagery. The abbreviation DN is the digital number recorded by the sensor in a satellite image. Radiation, on the other hand, is the amount of energy that the sensor receives from the Earth's surface.

$$L\lambda = \left(\frac{Lmax\lambda - Lmini\lambda}{QCALmax - QCALmini}\right) * (QCAL - QCALmini) + Lmini\lambda$$

i. L λ is spectral radiance

ii. L max λ is spectral radiance scaled to QCALMAX in (watt / (m^2 * s r*μm))

iii. L mini λ is spectral radiance scaled to QCALMIN in (watt / (m^{2}*s r*μm))

iv. QCAL is Quantized and calibrated standard product pixel (DN)

v. QCAL max is Maximum quantized calibrated pixel value (corresponding to Lmaxλ) DN

vi. QCAL mini is Minimum quantized calibrated pixel value (corresponding to L mini λ) DN

vii. L mini λ is spectral radiance scaled to QCALMIN in (watt / (m^2*s r*µm))

Step 2: Radiance to Brightness Temperature Conversion

Convert the radiance values from thermal band 6 to the brightness temperature at the sensor using the calibration coefficients provided. These coefficients are available in the metadata file for each Landsat scene.

$$BT = \frac{K2}{Ln\left(\frac{K1}{L\lambda} + 1\right)}$$

a. L λ is spectral radiance

b. K1 is the coefficient of Band 6 in Landsat 7(666.09)

c. K2 is the coefficient of Band 6 in Landsat 7(1282.71)

Step 3: BT Convert into Celsius degree

The most important step is to convert the at-sensor Brightness Temperature (BT) to Celsius degrees. This converter allows you to represent temperature in a more familiar and understandable unit.

$$C° = BT - 273.15$$

Land Use Land Cover: Land cover represents the physical type of land, such as forest or open water, while land use represents how people use the land. ArcGIS's Land Use Land Cover (LULC) classification uses remote sensing data, GIS tools, and image analysis techniques to classify various land cover types and land use activities within a geographic area. There are the following steps in land use land cover classification in Arc GIS 10.8.

Step 1: Data Preparation

Remote Sensing Data Collection: Get satellite or aerial images of the desired area. For accurate classification, high-resolution imaging with multispectral bands is preferred.

Georeferencing: Make sure your images are properly georeferenced to match the correct geographic coordinates.

Step 2: Image Preprocessing

Image Enhancement: I have Improved the visual quality of the image by applying techniques such as contrast correction, histogram equalization, and color balance of the study area.

Subset and Clip: To save processing time and focus on important data, clip the image to the exact area my study area in classifying.

Step 3: Training Data Collection

Ground Truth Data: I have collected ground truth data, which are typical samples of the various land cover types in my study area.

Training Sample Selection: I have Created polygons or points on my image that match the land use/land cover types in ground truth data using the ArcGIS tools. I collected the many training points in the study, then created specific classes and make a signature file.

Step 4: Classification

Supervised Classification: I have used a supervised classification method, such as Maximum Likelihood, Support Vector Machine, or Random Forest, to classify the image pixels into different land cover classes based on the training samples I collected.

Input Training Samples: I Provide the signature file created during the training data collection step as inputs to the classification algorithm.

Run Classification: Let the classification algorithm analyze the spectral features of study area image pixels and assign them to the appropriate land cover classes.

Step 5: Post Processing and Accuracy Assessment

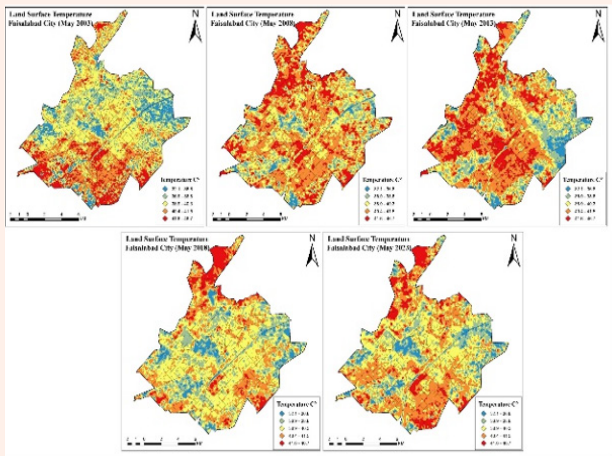
Image Smoothing: Apply post-processing techniques like majority filtering to smooth out small classification errors and enhance the overall map quality.

Accuracy Assessment: I have Performed an accuracy assessment by comparing the classified image with my ground truth data. which I have Calculated overall accuracy and class-specific accuracy to evaluate the reliability of my classification.

Step 6: Visualization and Interpretation

Create a Land Cover Map: Once I am satisfied with the accuracy of my classification, generate a land cover map that visually represents the different land cover types across the study area.

Figure 3: LST Map of Faisalabad City.



Step 7: Data Analysis and Reporting

Spatial analysis: I've used ArcGIS's spatial analysis tools to perform further analysis based on the classified map, such as calculating area statistics, identifying changes over time, or evaluating spatial patterns.

Create charts and graphs: Create a report documenting the classification methodology, accuracy assessment results, and key findings from the LULC analysis.

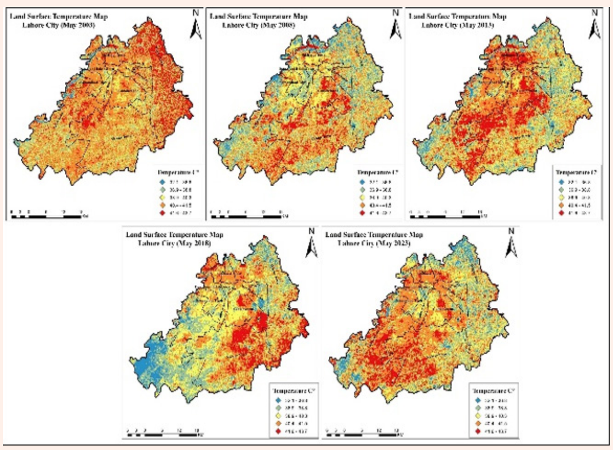
Results and Discussion

Land Surface Temperature

Land surface temperature (LST) is a critical climate parameter for understanding surface urban heat islands (SUHIs) in urban areas such as Faisalabad. Measured using remote sensing satellites, LST provides insights into the interactions between urbanization, land use, and temperature changes. Analysis of Faisalabad LST over the years 2003, 2008, 2013, 2018, and 2023 reveals significant temporal and spatial variations that shed light on the city's urban thermal dynamics and its evolving climate patterns.

In May 2003, LST in Faisalabad ranged from 31.2°C to 46.7°C, with the highest temperatures recorded in the southwestern part of the city due to sparse vegetation and barren land. In contrast, the northeastern region, influenced by the Gatwala forest, showed cooler temperatures. Similarly, in May 2008, the city experienced a temperature range of 32.1 °C to 46.7 °C. High temperatures were concentrated in the northern areas with limited green space, while the eastern areas near the Gatwala Forest Park remained relatively cooler. Urban areas, especially around the Agricultural University, showed a moderate temperature profile that highlighted the cooling effects of vegetation and open spaces. This trend continued in May 2013, with average LSTs between 40.39 °C and 45.39 °C. Dense urban areas characterized by impervious surfaces and limited vegetation recorded the highest temperatures, while suburban areas with more greenery showed lower LST values. Parks and agricultural fields in the southeastern outskirts of the city effectively mitigated the heat. By May 2018, the mean LST had slightly decreased to 39.9°C, but the urban cores continued to record high temperatures due to extensive human activity, impervious surfaces, and reduced vegetation cover. A significant temperature gradient emerged, with the suburban areas benefiting from mixed land use and green spaces that provided some cooling. Nighttime temperatures remained higher in the urban cores, underscoring the thermal stability of the built environment. In May 2023, the mean daytime LST increased to 42.7°C, with commercial and industrial areas often reaching temperatures above 45.6°C on clear days. The urban core again showed higher temperatures compared to the suburban and rural areas, which showed a gradual cooling effect due to the combination of built spaces and vegetation cover. The industrial and wasteland areas of the northeast near Sargodha Road remained hot spots during the study period. Climatic factors such as cloud cover and wind patterns played a significant role in moderating daytime temperatures and creating local cooling in specific areas.

Figure 4: LST Map of Lahore City.



Overall, the analysis highlights the persistence of the urban heat island (UHI) effect in Faisalabad, with urban, barren and industrial areas consistently recording higher LST values compared to suburban and rural areas. Green spaces and agricultural lands emerged as very important temperature buffers, underscoring their role in reducing urban heat gain. These findings highlight the urgent need for sustainable urban planning to counter the effects of rising temperatures. Strategies such as increasing green infrastructure, promoting energy-efficient construction and implementing heat reduction programs, such as urban forestry, are essential. By adopting these measures, Faisalabad can increase its resilience to climate change, improve local climate conditions and ensure the well-being of its residents. Analysis of land surface temperature (LST) in Lahore city provides a comprehensive understanding of urban thermal characteristics and dynamics, revealing significant insights into how land use, vegetation and urbanization affect temperature distribution. Using advanced remote sensing techniques and spatial analysis, the study highlighted trends across years, highlighting the urban heat island (UHI) effect and its implications for urban planning and sustainability.

In May 2003, LST ranged from 32.1°C to 43.7°C, with the highest temperatures observed in the central areas of the city due to low vegetation, high impervious surfaces and increased human activity. The Ravi River and its surrounding green spaces reduced temperatures in the northern and northwestern regions. Similarly, in May 2008, central Lahore recorded the highest LST values, while the presence of vegetation in the suburban and rural areas contributed to moderate temperatures. The study highlighted the thermal variability associated with land use patterns, noting that commercial and industrial areas consistently exhibited high temperatures.

As of May 2013, LST values continued to range from 32.1°C to 43.7°C, showing a clear contrast between densely built-up areas and areas rich in vegetation. Green spaces and suburban areas recorded cooler temperatures due to shade and evapotranspiration effects, while dense urban surfaces enhanced heat retention. Notably, the analysis drew attention to the importance of green infrastructure in mitigating UHI effects and enhancing urban livability. The LST analysis for May 2018 showed a similar pattern, with Iqbal Town exhibiting the lowest temperatures due to its well-distributed vegetation and green spaces. In contrast, dense downtown development continued to increase LST values. The study highlighted Iqbal Town as a model for integrating green infrastructure into urban design, demonstrating its effectiveness in reducing heat and improving thermal comfort.

In May 2023, spatial heterogeneity in LST values persisted with temperatures ranging from 32.1°C to 43.7°C. Wagah Town in the northern region exhibited the lowest LST due to its proximity to open spaces and cooler rural air masses. Conversely, Iqbal Town exhibited the highest temperature, reflecting its dense urban environment and limited green space. These findings underscore the critical role of local urban design and environmental factors in shaping thermal patterns.

Over the years, the analysis consistently demonstrated the impact of vegetation cover in moderating LST, while impervious surfaces and dense urbanization exacerbated heat retention. The study advocates sustainable urban planning strategies, such as increasing green spaces, implementing cool roof technologies, and adopting energy-efficient designs to combat the effects of UHI. The contrasting thermal behaviors of areas such as Wagah Town and Iqbal Town emphasize the need for appropriate interventions to enhance urban resilience and create livable environments in Lahore amidst rising global temperatures.

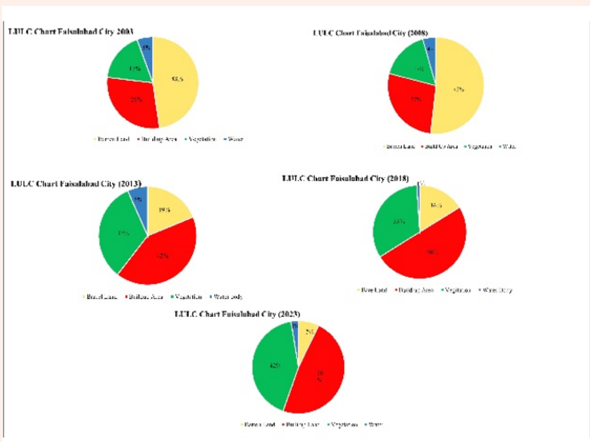
Land Use Land Cover

The results of the land use and cover (LULC) classification process provide valuable insights into the spatial distribution and dynamics of different land use categories in Faisalabad. These classifications revealed distinct land use patterns and highlighted the complex interactions between human activities and the environment. Agricultural land emerged as an important category, underscoring the region's reliance on agricultural activities. However, the variation in the extent and distribution of agricultural areas reflects the spatial heterogeneity of land use practices, with implications for food production, rural livelihoods, and land management strategies. The classification also identified natural land covers such as forests, water bodies, and open spaces, the conservation of which is critical for maintaining ecosystem services, mitigating climate change, and enhancing environmental quality

In May 2003, Faisalabad's LULC data showed that wasteland areas constituted 48 percent of the city's total land area, likely due to natural topography, soil conditions, or poor urban development. Built-up areas including residential, commercial and industrial areas account for 29%, reflecting moderate urbanization and infrastructure growth. Vegetated areas cover 17%, reflecting limited green spaces that are essential for air quality, biodiversity and urban beauty. Water bodies account for 7% of the land, indicating the presence of canals and ponds that require sustainable management to prevent pollution and support local ecosystems.

By May 2008, wasteland had slightly decreased to 42%, while built-up areas had increased to 37%, reflecting ongoing urbanization driven by population growth and economic activity. Vegetated areas remained stable at 17%, highlighting the need for enhanced green infrastructure. Water bodies declined by 4%, likely due to urban encroachment or changes in water management practices, underscoring the importance of conserving these vital resources. The dynamic changes in LULC in 2008 highlighted the challenges of managing urban sprawl while maintaining environmental quality.

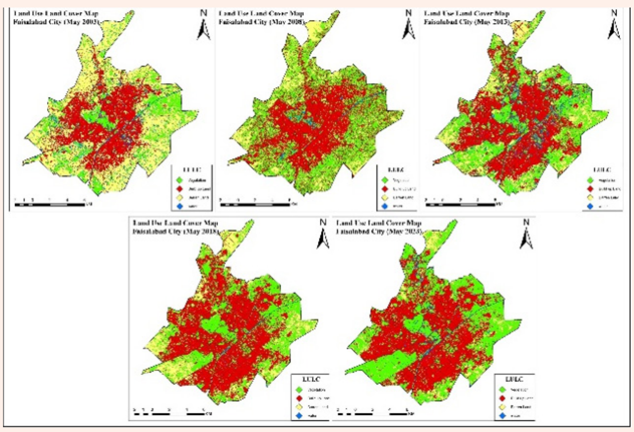
Figure 5: LULC Map of Faisalabad City.



In May 2013, the city witnessed further transformation, with built-up areas increasing to 42%, reflecting rapid urbanization. Vegetated areas increased to 33%, reflecting efforts to integrate green spaces into the urban fabric, which has a positive impact on biodiversity and environmental health. Water bodies account for 6% of the land area and maintain their ecological importance. Wasteland decreased significantly to 19%, reflecting urban regeneration and optimization of underused spaces. These trends underscore the importance of sustainable urban planning to strike a balance between development and environmental protection. By May 2018, built-up areas had increased to 48%, reflecting a period of rapid growth. Vegetated areas remained stable at 33%, highlighting the preservation of green spaces amidst urbanization. Water bodies decreased to 3%, raising concerns about water resource management and conservation. Wasteland decreased to 16%, indicating ongoing efforts to convert vacant spaces to productive use. The period highlighted the critical need for integrated urban planning that addresses infrastructure needs while conserving natural resources and green areas.

In May 2023, Faisalabad's LULC patterns showed significant improvements. Built-up areas accounted for almost 50% of the total land, reflecting increasing urbanization driven by population and economic pressures. Vegetated areas increased significantly to 42%, indicating successful initiatives to expand green spaces and improve environmental resilience. However, water volume decreased to only 1%, indicating the urgent need for sustainable water management practices to reduce scarcity and pollution. Wasteland decreased to 7%, reflecting effective land reclamation strategies. These changes underscore the need for strategic urban planning that prioritizes green infrastructure, water conservation, and sustainable growth to create a resilient and livable urban environment.

Figure 6: LULC Chart of Faisalabad City.



The evolving patterns of LULC in Faisalabad over two decades highlight a dynamic urban landscape and the critical need for responsive policies. Balancing development with environmental sustainability is key to ensuring long-term resilience. Regular monitoring of land cover changes provides essential data to guide decision-making, adapt strategies, and achieve sustainable urban growth. The Land Use and Cover (LULC) analysis of Lahore city, conducted over the years, provides important insights into the dynamic transformation of its urban landscape. This comprehensive classification provides a detailed description of the distribution and composition of different land categories, reflecting the trends of urbanization, environmental protection and resource management. In May 2003, the LULC classification of Lahore showed that built-up areas covered approximately 33 percent of the total land area of the city, indicating rapid urban growth and infrastructure development. Vegetation accounted for 34 percent, highlighting its ecological importance in reducing urban heat, improving air quality and creating recreational spaces. Wasteland accounted for about 32 percent, highlighting underutilized spaces with the potential for productive transformation. Water bodies, occupying only 1 percent, emphasized the limited presence of natural aquatic features, which are vital for biodiversity and water management. These results underscored the need for balanced urbanization and informed planning strategies.

By 2008, built-up areas had decreased to 25 percent, reflecting a shift towards efficient land use practices and sustainable development. Vegetation cover had increased to 40 percent, reflecting efforts to improve air quality and support biodiversity. Wasteland remained stable at 33 percent, reflecting persistent underutilized spaces that require strategic re-use. Water bodies continued to cover 1 percent and maintained their importance for ecological and recreational needs. These changes reflected urban efforts to balance urban growth with environmental well-being. A 2013 analysis showed an increase in residential areas to 38 percent, driven by population growth and economic demands. Vegetation cover increased slightly to 41 percent, reflecting commitment to green spaces despite urban pressures. Wasteland decreased to 19%, indicating successful land management initiatives, while water bodies increased to 2%, indicating conservation efforts. The findings highlighted Lahore's different approaches to sustainable urbanization and environmental stewardship.

By 2018, built-up areas had increased significantly to 43%, indicating ongoing urban development. Vegetation cover decreased to 23%, raising concerns about environmental quality and emphasizing the need for green infrastructure. Wasteland remained stable at 32%, while water bodies maintained their 2% coverage. The results highlighted the challenges of managing urban growth while preserving ecological balance and natural resources. The most recent classification in 2023 showed built-up areas occupying 44%, highlighting rapid urbanization. Vegetation covers further decreased to 26%, warning planners about the potential impacts on air quality and residents' well-being. Wasteland increased to 28%, indicating the need for improved land use strategies. Water volume remained at 2%, highlighting their environmental and recreational importance. These trends underscore the importance of integrating sustainability and environmental protection into urban planning.

Figure 7: LULC Map of Lahore City.

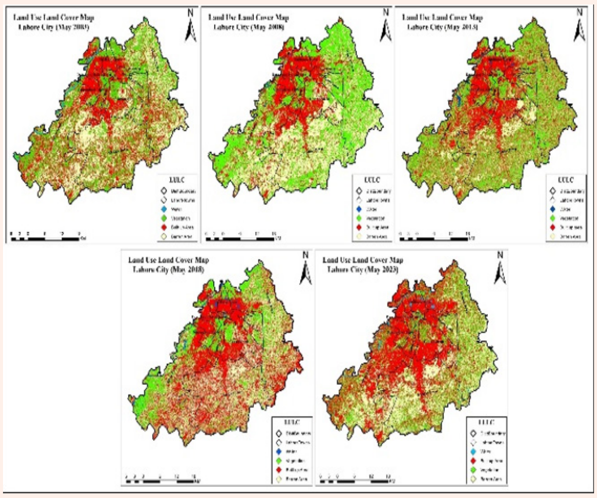
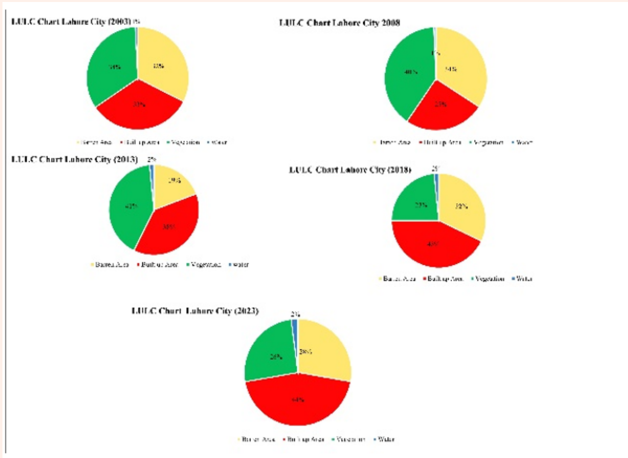


Figure 8: LULC Chart of Lahore City.



Overall, the evolving LULC patterns of Lahore city highlight the interplay between development, environmental protection and resource management. Each analysis provides important insights for urban planners and policymakers to guide sustainable growth and ensure a resilient, livable and balanced urban environment for current and future generations.

Comparison

A comparative analysis of land surface temperature (LST) and land use/land cover (LULC) patterns in Faisalabad and Lahore from 2003 to 2023 highlights several common trends and distinct differences in urban heat dynamics, land use changes, and environmental impacts. The need for sustainable urban planning in both cities Urban Heat Island Effect (UHI): Both Faisalabad and Lahore have a strong urban heat island effect (UHI), with urban areas consistently exhibiting higher LST values compared to suburban and rural areas. In Faisalabad, urban, barren, and industrial areas reached temperatures above 46°C, largely due to extensive impervious surfaces and reduced vegetation cover. Similarly, commercial and industrial areas in Lahore experienced the highest LST values. Both cities experienced the cooling effect of green spaces in suburban and rural areas, where the balance of built-up areas and vegetation helped maintain more moderate temperatures. Despite these cooling zones, urban cores in both cities consistently exhibit high temperatures, indicating the persistence of the UHI effect.

Temporal and spatial LST trends: In both cities, LST fluctuations over the years show a growing trend of heat accumulation in densely built-up areas. For Faisalabad, LST remains high throughout the day, even at night, highlighting the continuous nature of the UHI effect. Lahore showed similar patterns, with areas with abundant vegetation consistently maintaining cooler temperatures, underscoring the importance of green infrastructure in reducing urban heat. The southeastern suburbs of Faisalabad, with agricultural lands and open spaces, benefit from natural cooling, which is in line with the neighborhoods and parks of suburban Lahore that exhibit lower LST values. In both cities, targeted interventions, such as enhancing green infrastructure and implementing heat-reduction strategies, are needed to address rising urban temperatures.

Land Use and Land Cover Changes: LULC trends in Faisalabad indicate that built-up areas will occupy 50% of the total city area by 2023, reflecting rapid urbanization driven by population growth and economic development. However, this growth has come at the cost of loss of natural land, particularly agricultural fields and forests, raising concerns about loss of biodiversity and ecological balance. In contrast, Lahore's built-up area increased from 33% in 2003 to 44% in 2023, while vegetation cover decreased from 34% to 26%. This trend in Lahore indicates a greater loss of green space compared to Faisalabad, indicating a more urgent need for strategies to preserve and expand green space.

Faisalabad showed a significant increase in vegetated areas, reaching 42 percent by 2023, and a decrease in barren lands, which decreased to just 7 percent. This suggests that Faisalabad is making efforts to integrate green spaces into the urban landscape. Conversely, Lahore saw a decline in vegetated areas, reaching only 26 percent by 2023, while barren lands continued to decline like Faisalabad, although the overall rate of land change in Lahore appeared to be more detrimental to the greenness of the city.

Water bodies and environmental sustainability: The reduction of Faisalabad's water bodies to just 1 percent of the land area by 2023 highlights a critical challenge in sustainable water management, exacerbated by urban sprawl. Lahore also faced similar challenges, although trends in both cities highlight the importance of conserving water bodies amidst urban growth. Water conservation strategies are essential for both cities to ensure long-term environmental sustainability and resilience. Urban design and sustainable practices: In Faisalabad, areas such as the South-East Suburbs and Iqbal Town, which benefited from green infrastructure, showed lower LST values, highlighting the role of sustainable urban design in reducing urban heat. The Lahore LST analysis also showed that areas with significant vegetation cover, such as parks, help reduce temperatures. Both cities should prioritize green infrastructure, energy-efficient buildings, and heat-reduction strategies such as cool roofs and reflective surfaces to reduce the UHI effect and increase live ability.

Conclusion

While both Faisalabad and Lahore face similar challenges related to urban heat accumulation and land-use change, Faisalabad has shown limited success in maintaining and expanding green spaces compared to Lahore's rapid loss of vegetation. However, both cities need comprehensive urban planning to balance growth with environmental protection. Effective strategies to integrate green space, sustainable water use, and energy-efficient infrastructure will be crucial in ensuring the long-term resilience and livability of both cities in the face of climate change and urbanization pressures.

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