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Relationship between Land Use Land Cover and Land Surface Temperature in the Formation of Urban Heat Islands across Pakistan

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Abstract

Urbanization drives economic growth and technological progress, but unplanned expansion leads to environmental degradation, loss of Urban Green Spaces (UGS), and the generation of Urban Heat Islands (UHI), adversely affecting ecological systems and public health. This study aimed to (1) identify land cover change patterns across Pakistan's major climatic zones and assess their impact on Land Surface Temperature (LST) to generate UHI for 2019 by Getis-Ord Gi* hotspot analysis, and (2) consolidate sustainable urban development strategies amid rapid urbanization, population growth, and expanding megacities. Landsat OLI-TIRS (Operational Land Imager-Thermal Infrared Sensor) imagery for 2019 and climatic data were analyzed using supervised classification, NDVI-based LST retrieval, and hotspot analysis. Results show LST ranged from –26 °C in northern high-altitude regions to ~50 °C in southern and central plains. Zones B–E experienced strong to very strong UHI exposure, with built-up areas reaching ~50 °C, barren land ~48 °C, and sparse vegetation ~34 °C, while dense vegetation remained the coolest at ~27 °C. Bibliometric analysis of 287 publications (2006–2021) revealed increasing global research on UGS–LST–UHI relationships, though international collaboration remains limited. Findings underscore the critical role of green infrastructure and climate-sensitive urban planning in mitigating UHI and promoting resilient, sustainable urban development.

***Keywords*:** Urban Heat Islands; Land Surface Temperature; Land Use Land Cover; Bibliometric; Urban Green Spaces; VOS Viewer

1. Introduction

Urbanization, a global phenomenon, can evidently be seen in the developing world (Garcia-Garcia et al., 2020; United Nations, 2018). As urban centers are hubs of entrepreneurship and innovations hence, better employment opportunities and more per capita income are linked to urbanization. However, according to studies, this relationship is not generated automatically but must be in a sustainable manner, as its benefits can only be achieved sustainably (Kousar et al., 2018). Urban Green Spaces (UGS) are the diverse green patches in urban areas and the source of fresh air; however, the most affected places due to changes in ecological patterns and commercial development (Liu et al., 2023; Cai et al., 2019; Breuste et al., 2008). The outcome of the reduction in UGS is the significant increase in surface temperature that results in the generation of Urban Heat Island (UHI) (Ramaiah and Avtar, 2019; Bounoua et al., 2015; Ugle et al., 2010). Generation of UHI alters the Surface energy balance and radiation budget of the planet, which must be regulated to maintain air quality and regulate microclimate (Ramaiah and Avtar, 2019; Melaas et al., 2016; Qian et al., 2015).

UHI has been studied traditionally for isolated locations through in situ air temperature measurements. However, with the onset of satellite remote sensing, it has become possible to investigate and generate the UHI phenomenon on a continental as well as a global scale (Melaas et al., 2016; Streutker, 2002). Calculating Land Surface Temperature (LST) is the prime method to generate UHI. Research has shown that the surface radiant temperature response, due to the partitioning of latent and sensible heat fluxes, causes variations in vegetation cover and surface soil water content (Alharbi et al., 2022; Jensen et al., 2005; Weng et al., 2004; Oke, 1982). Sparse vegetation of urban areas favours sensible heat exchange, while latent heat exchange is found with more vegetated areas (Weng and Lu, 2008; Weng et al., 2004). Such findings led more researchers to focus on the relationship between LST and UGS and to use the physical and remote parameters, i.e., ground station temperature records and satellite data for land cover change analysis and LST (Terfa et al., 2020; Yao et al., 2020; Masoudi et al., 2019; Cha et al., 2019; Heinl et al., 2015). LST is a major parameter that is associated with surface radiation and energy exchange. It can modulate the air temperature layer directly above the Earth's surface (Mostovoy et al., 2006). Hence, LST has been widely used by researchers to study the spatial patterns of UHI and its relationship with UGS (Terfa et al., 2020; Masoudi et al., 2019).

Consolidated efforts have been made by many researchers around the world to explain the importance of UGS for minimizing the LST and UHI over the last two decades (Liu et al., 2023; Fu et al., 2022; Tian et al., 2021; Masoudi and Tan, 2019). The main subjects discussed by researchers are thermal heat comfort, UHI, and mitigation of heat (Yang et al., 2016; Tian et al., 2021). Other focuses are about the cooling effect of UGS, urban landscape planning and design, how to plant UGS to lower LST while energy consumption and mitigation techniques were also discussed by some authors over the last two decades. Inquiring techniques and methods used have also been discussed and changed (Hayes et al., 2022; Almeida et al., 2021; Mirzaei, 2015). During this time period, little attention was paid before 2014, while a steady increase has been observed after 2016 in the importance of UGS for the urban cooling effect. The continuous rise in urban temperature globally and awareness about the importance of greenery are the basic reasons for the increase in work in this research domain. Despite the phenomenal increase in awareness, research, and scholastic efforts about the importance of UGS for LST and UHI, some review papers have also been retrieved that have attempted to review the research work for this domain (Almeida et al., 2021; Kim and Brown, 2021; Hami et al., 2019; Deilami et al., 2018; Rasul et al., 2017; Ngie et al., 2014; Weng, 2009). However, all of these studies deployed the bibliometric analysis to review urban greenery with land surface temperature.

However, despite these extensive studies, there remains a lack of integrated research that combines national-scale remote sensing–based UHI assessment with bibliometric analysis. In particular, no study has comprehensively examined the relationship between Land Use Land Cover (LULC) and Land Surface Temperature (LST) for Urban Heat Island (UHI) formation across different climatic zones of Pakistan at a national scale. Furthermore, the linkage between empirical spatial analysis and global research trends on UGS–LST–UHI relationships remains largely unexplored. This study addresses these gaps by providing a climatic-zone–based national-scale assessment integrated with a bibliometric perspective, thereby offering both local and global insights.

Within this broader research context, developing countries such as Pakistan are experiencing accelerated land cover transformation due to rapid urban expansion, population growth, and infrastructural development. Given Pakistan's pronounced climatic heterogeneity, land cover change does not manifest uniformly across regions, making climatic zone–based analysis essential. Such transformations have direct implications for Land Surface Temperature (LST) and the intensity of Urban Heat Island (UHI), particularly in urban and peri-urban settings.

As the generation of UHI and increasing land surface temperatures continue to impact public health as well as flora and fauna at a global scale (Kondo et al., 2018; Jennings et al., 2016), there is an urgent need to advance environmentally and ecologically sustainable urban development strategies. In this context, the present study is designed to examine both the empirical and global dimensions of the UGS–LST relationship. Specifically, the bibliometric analysis evaluates research trends, key thematic areas, publication patterns, and collaborative networks in UGS–LST studies over the period 2006–2021, including the geographical distribution of research productivity and international cooperation among authors and institutions. To ensure conceptual coherence, this study adopts a structured approach that integrates empirical analysis with a global research perspective. The research is primarily grounded in remote sensing–based analysis, which provides spatially explicit, Pakistan-focused evidence of LULC–LST interactions and their role in UHI formation. Complementing this, a bibliometric component is incorporated to examine the global research landscape of UGS–LST studies, identifying prevailing research trends, methodological approaches, collaboration networks, and established mitigation strategies. Accordingly, the objectives of this study are:

1) To analyze the patterns of Land Use Land Cover (LULC) across major climatic zones of Pakistan and examine their impact on Land Surface Temperature (LST) for the assessment of Urban Heat Island (UHI) in 2019;
2) To conduct a bibliometric analysis of UGS–LST–UHI research (2006–2021) to identify global research trends, thematic focus areas, and collaboration patterns, and to support sustainable urban development insights in the context of rapid urbanization.

2. Materials and Methods

The study adopts an integrated methodological framework that combines empirical analysis with a global research perspective to enhance the understanding of urban heat island (UHI) dynamics. The study area comprises Pakistan, covering a total land area of 880,940 km² and located between latitudes 24°–37°N and longitudes 60°–75°E. Remote sensing–based methods were employed to assess land cover changes and LST-driven UHI patterns across Pakistan's climatic zones (Fig. 1), providing spatially explicit, country-level evidence. To support the interpretation of these findings, a bibliometric analysis of UGS–LST research was conducted to identify global research trends, publication patterns, and collaboration networks. In this context, the bibliometric component serves to contextualize the empirical results rather than function as an independent analysis. Furthermore, co-occurrence and network analyses were used to map collaborations among countries, institutions, and authors, as well as citation patterns, thereby linking global knowledge structures with insights derived from the Pakistan case study. The study integrates bibliometric analysis with remote sensing-based geospatial assessment to provide both scientific and spatial perspectives on urban heat island research. The bibliometric component identifies major research trends, themes, and knowledge gaps in UHI and LST studies, while the remote sensing analysis provides empirical evidence of spatial temperature variation and urban thermal characteristics within the study area. The integration of these two approaches improves the overall understanding and contextual interpretation of the findings. A detailed description of the study area is provided in Table 1, while its spatial distribution is illustrated in Figure 1. The detailed methodology is presented in Figure 2.

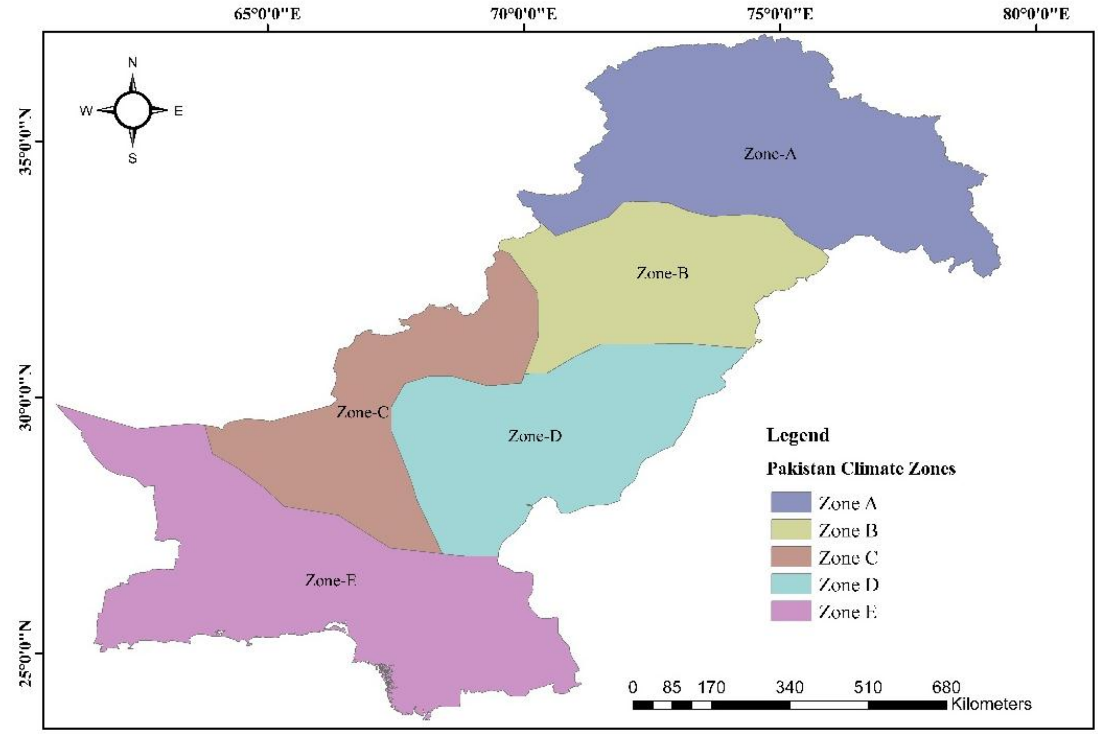

Fig. 1 Study area map of Pakistan

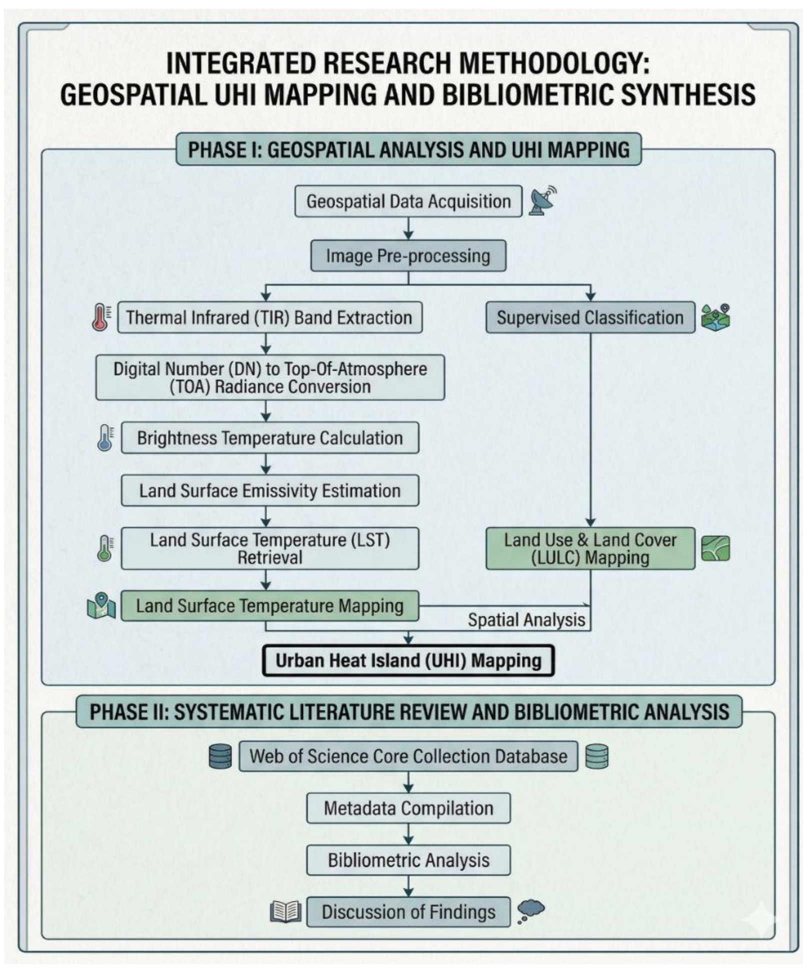

Fig. 2 Methodological Framework of remote sensing–based UHI analysis and bibliometric analysis.

Table 1: Climatic zones of Pakistan (Qasim et al., 2014)

Sr #	Climatic Zones	Description and Features
1	**Zone A**	This zone has cold climatic conditions and high, elevated mountains. It is situated in the North of Pakistan, located between 34°N to 38°N and 70°E to 78°E in the Hindukush Himalayan ranges.
2	**Zone B**	The zone is located between 31°N to 34°N and 70°E to 75°E with mild climatic conditions and sub-mountains.
3	**Zone C**	This zone is located between 27 N º to 32 N º and 64 E º to 70 Eº. It is a mountainous zone with high elevation, and here the weather is cold in winters and hot in summers.
4	**Zone D**	The hottest and driest climatic zone of Pakistan, having high mean temperatures, located between 27 N º to 31 N º and 67 E º to 7 Eº.
5	**Zone E**	It is the biggest zone of Pakistan with coastal cities and the Arabian Sea. The coastal region is subdivided into a small portion of Baluchistan province and arid Sindh province. It is located between 24 N º to 31 N º and 61 E º to 71 Eº.

2.1. Data Acquisition

2.1.1. Geospatial Data Acquisition

Satellite data acquired from earthexplorer.usgs.gov and climatic data acquired from PMD (Pakistan Meteorological Department) were used in this study. OLI-TIRS Landsat satellite data and daily climatic data were collected for 2019. The year 2019 was selected as a representative year due to the availability of high-quality, cloud-free Landsat 8 imagery, enabling consistent national-scale analysis of LULC–LST relationships and UHI spatial patterns. The path/row followed by L8 OLI-TIRS was 157/40 to 145/34. Salient characteristics of satellite images deployed in the study are shown in Table 1.

Table 2: Salient characteristics of satellite images deployed in the study.

Satellite	Sensor(s)	Path/Row	Year	Spatial Resolution	Spectral Bands	Temporal Resolution
Landsat 8	Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS)	157/40 145/34	2019	30 m (visible, NIR, SWIR); 15 m (panchromatic); 100 m (thermal)	11 bands	16 days

2.1.2. Web of Science core collection

The literature used in the current study was exported from the databases of Web of Science (WoS). The terms "Urban Green Spaces and Land Surface Temperature" were used as topical retrieval, while the time span was set for twenty years between 2006 and 2021, and English was selected as the language. The types of documents were limited to articles, proceedings, letters, and review papers. The literature type, time span, and language were set to avoid digressions. There were 287 documents with 5 types retrieved with the selected criteria. The document types included articles (239), Proceedings papers (31), early access articles (11), Review (5), and Letter (1). The most frequent type of document is articles with a proportion of 83.2% of total publications, while proceedings papers were second with 10.8% proportion. The type, number, and proportion of retrieved documents have been listed in Table 2.

Table 3: Type of retrieved document.

Document Type	Frequency	Proportion
Article	239	83.28%
Proceedings	31	10.8%
	11	3.83%
Review	5	1.74%
Letter	1	0.345%
Total	*287*	*100*

2.2. *Data Analysis*

2.2.1. Remote Sensing–Based Methodology for Urban Heat Island (UHI) Analysis

2.2.1.1 Image Preprocessing

Analysis was performed in a series of steps involving the preparation and processing of data with the help of different software, viz., ArcMap 10.3, ERDAS Imagine 2014, Google Earth, and Microsoft Excel. Satellite images were subjected to atmospheric and geometric correction for removal of cloud cover and image enhancement. Atmospheric correction was performed using the Dark Object Subtraction (DOS) method to minimize atmospheric scattering effects. Radiometric correction was applied in ERDAS IMAGINE 2014 to convert raw digital numbers into at-sensor radiance and brightness temperature, ensuring consistency in the spectral and thermal properties of the satellite data.

2.2.1.2 Supervised Classification

After pre-processing, supervised classification was applied to the satellite image. Eight LULC classes were formed, namely Built Up, Agricultural Land, Dense Vegetation, Sparse Vegetation, Barren land, Shrub Land, Water, and Snow (detailed description is shown in Table 3). The objects were placed in a specific class with the best match, and then the classification process was executed using the maximum likelihood algorithm. Due to the large spatial extent of the study area, field-based ground truthing was not feasible. Therefore, high-resolution Google Earth imagery, supported by existing land use/land cover maps, was used for visual validation of the classified results. This approach is widely adopted in large-scale remote sensing studies where field access is limited. Finally, accuracy assessment was done where a total of 100 validation points were used for accuracy assessment, and the classification results yielded an overall accuracy of 87% with a Kappa coefficient of 0.84, processed using ERDAS IMAGINE 2014.

Table 4: Land Cover Type and description.

Class name	Description
Built Up	Commercial buildings, residential blocks, roads, bridges and other infrastructure.
Agricultural land	Areas used for cultivation and agricultural purposes, including farms and plantations.
Dense Vegetation	Areas with high-density tree cover, thick forests, and other lush vegetation typically found in parks, greenbelts, or natural reserves.
Sparse vegetation	Areas with scattered or low-density vegetation, including grasslands and bushes.
Barren Land	Includes barren land, rocks, desertified land, and fallow land.
Shrub Land	Dominated by shrubs, small woody plants, and scattered bushes.
Water	Rivers, lakes, dams, small streams and nullahs.
Snow	Areas covered by snow, including glaciers and snowfields.

2.2.1.3 Land Surface Temperature Retrieval

The Land Surface Temperature (LST) is the temperature of Earth's surface at a given time and gives information about the thermal characteristics of different land cover classes (Mallick et al., 2008). Before calculating LST, Digital number values of pixels have to be converted into spectral radiance because the Digital number value stores the radiance but gives no information itself (Shah and Ghauri, 2015). LST of the study area was calculated from the TIR (Thermal Infra-Red) band of Landsat. LST was retrieved using the Single Channel Algorithm (SCA) based on Planck's radiative transfer equation. Landsat 8 Thermal Infrared Sensor (TIRS) Band 10 was used for temperature calculation. LST was retrieved using the Single Channel Algorithm (SCA) based on Planck's radiative transfer equation. Landsat 8 Thermal Infrared Sensor (TIRS) Band 10 was used for temperature calculation. The process involved standard thermal band processing of Landsat data, with emissivity correction applied using an NDVI-based approach to account for land cover heterogeneity across the study area. Planck's equation (Artis and Carnahan, 1982) used for deriving LST is as follows:

$$\boldsymbol{St} = \frac{T}{1} + \left(\lambda \times \frac{\mathrm{T}}{\rho}\right) \ln \in \quad \text{..........}\textbf{(1)}$$

In the above equation, St is the Land Surface Temperature; T is the brightness temperature, λ is the wavelength of the TIR band, and $\in$ is the land surface emissivity. Moreover, ρ is equal to h/cσ, where h is Planck's constant, c is the velocity of light, and σ is the Stefan's constant. ρ = 0.01438 mk.

For brightness temperature (T), the following equation was used:

$$\mathbf{T} = \frac{\mathbf{K2}}{\mathbf{In}\left(\frac{\mathbf{K1}}{\mathbf{L\lambda}} \mathbf{+1}\right)} \quad \text{..........}\textbf{(2)}$$

Here, K_2 and K_1 are band-specific constants determined by the wavelength of the sensor, whereas L_λ is the surface radiance, which was calculated by the following equation:

$$\mathbf{L\lambda} = \left[\frac{\mathbf{Lmax - Lmin}}{\mathbf{QCALmax - QCALmin}}\right] \times (\mathrm{DN} - \mathrm{QCALmin}) + \mathrm{Lmin} \quad \text{..........}\textbf{(3)}$$

Here, L_{max} and L_{min} are maximum and minimum radiation, DN is the pixel value of DN, and $QCAL_{max}$ and $QCAL_{min}$ are calibrated energies whose values are 1 and 255, respectively. After calculating the radiance and brightness temperature, Emissivity was calculated by using NDVI through the equation mentioned below. Emissivity was estimated using an NDVI-based vegetation proportion method to account for land surface heterogeneity across different land cover types.

$$\in = 0.004PV + 0.986 \quad \text{..........}\textbf{(4)}$$

PV stands for the proportion of vegetation and was calculated as follows:

$$\boldsymbol{PV} = \left[\frac{\boldsymbol{NDVI - NDVImin}}{\boldsymbol{NDVImax - NDVImin}}\right] 2 \quad \text{..........}\textbf{(5)}$$

The NDVI values used for emissivity estimation were derived from atmospherically corrected Landsat 8 imagery, with NDVI min and NDVI max calculated from the study area as the minimum and maximum observed NDVI values, respectively (Dwivedi et al., 2019):

$$\boldsymbol{NDVI} = \frac{NIR\ Band - RedBand}{NIR\ Band + RedBand} \quad \text{..........}\textbf{(6)}$$

Then, LST was retrieved by using equation 1 and compared with ground station-based temperature data to determine the accuracy.

2.2.1.4 Spatial Analysis for UHI generation

The Hot-Spot Analysis tool's final outputs were the major hot and cool locations, as specified by the following formula using default spatial weight settings in the GIS environment to identify statistically significant clusters of high and low Land Surface Temperature (LST) values.

$$\mathrm{G}_i^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{x}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\left[\frac{n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}\right]}} \quad \text{..........}\textbf{(7)}$$

$$\bar{\mathbf{X}} = \frac{\sum_{j=1}^{n} x_j}{n} \quad \text{..........}\textbf{(8)}$$

$$\mathbf{s} = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \quad \text{..........}\textbf{(9)}$$

Where n is the total number of features, wi,j is the spatial weight between features I and j, and xj is the attribute value for feature j (7, 8). The values X and S represent the mean and variance, respectively. Here: $\bar{x}$ represents the mean value of the surface temperature over all **n** features, and *S* is the standard deviation (9), a measure of the dispersion of temperature values across the region.

Finally, by using Getis-Ord Gi* statistics for surface temperature in context with neighboring cell temperatures, hotspot analysis of the research region has been computed. The Gi* value, which is a z-score, displays the clustering of features with high or low values (Guerri et al., 2021:Grigoraș & Urițescu, 2018). The five levels correlate with LST values assigned to them; the "very high" and "very low" classes, which designate the locations with extreme values, are the most relevant for studying. Finally, zonal statistics were applied to generate a UHI graph using Adobe Illustrator.

2.2.2. Systematic Literature Review and Bibliometric Analysis of Urban Green Spaces (UGS) and Land Surface Temperature (LST)

2.2.2.1 Metadata Compilation and Bibliometric Analysis

Bibliometric analysis can be performed using various software (Afuye et al., 2024; Garousi and Mäntylä, 2016; Powell et al., 2016). Visualization science mapping can represent the development status and discipline situation and is significant for bibliometrics (Powell et al., 2016). VOS Viewer, a free software developed by Nees Jan van Eck and Ludo Waltman at the Centre for Science and Technology Studies, Leiden University, Netherlands (Liao et al., 2018), and Olle Persson, a Swedish information scientist, respectively, has been used for visualization mapping of this research work. Each software involved in the bibliometric analysis has its own specific functions and gives advantages in one or other way. For instance, VOS Viewer is one of the friendly graphical user interfaces that enables the visualization and networking of the generated map easily (Cobo et al., 2011), while BibExcel has the ability to handle big data (Persson et al., 2009). For the current study, the bibliographic networks, including Co-citation analysis of authors, co-occurrence of keywords, and co-authorship analysis, were performed in VOS Viewer software, and network maps were generated. VOS stands for Visualization of similarities and is used to generate both visual and quantitative information in the relevant field of research (Van Eck and Waltman, 2010). Bibexcel was used to generate and manage a large amount of data to depict bibliometric indicators, including country-wise publications, spatio-temporal analysis of published articles, top ten authors, journals, and organizations. Microsoft Excel was then used to draw graphs and charts.

3. Results

The results and discussion section is divided into two sections, first describing the UHI based on LULC and LST for Pakistan, and then the second section describes the findings of the bibliometric analysis about UGS and LST.

3.1 Results of Remote Sensing–Based Urban Heat Island (UHI) Analysis

3.1.1 Land Use Land Cover Mapping

The land cover distribution in 2019 across Pakistan's major climatic zones shows a pronounced dominance of shrub land and barren surfaces, accompanied by significant urban expansion and reduction in vegetated areas. Shrub land constitutes the largest share, covering 31.68% of the total area, followed by barren land (26%) and agricultural land (25%), indicating extensive dry and semi-arid landscapes across the country. This dominance of dry land surfaces reflects the prevailing arid and semi-arid climatic conditions of Pakistan, which are highly susceptible to heat accumulation and environmental degradation under increasing urban pressure. Dense vegetation accounts for 10.86%, while sparse vegetation covers 3%, reflecting a substantial decline in continuous vegetation cover, particularly in climatically stressed and urban-influenced zones. Built-up areas, although occupying a relatively small proportion (0.50%), represent a critical indicator of rapid urban expansion concentrated in major urban and peri-urban regions, as shown in Figure 3 and Table 4. Although the percentage of built-up area appears relatively low at the national scale, its concentration around major urban centers significantly influences local thermal environments and contributes to surface heat intensification. Water bodies and snow/ice cover occupy 0.73% and 2.24%, respectively. The reported 0.50% built-up area represents the national-scale land use/land cover distribution of Pakistan, where urban land occupies a relatively small proportion compared to other dominant land cover classes such as agriculture, barren land, vegetation, and mountainous regions. Therefore, this value reflects overall national composition rather than urban intensity. These land cover characteristics in 2019 have important environmental implications, as the expansion of built-up areas and reduction in vegetated surfaces contribute to elevated Land Surface Temperature (LST) and the intensification of the Urban Heat Island (UHI) phenomenon. This transition from natural to impervious surfaces reduces the landscape's thermal regulation capacity and enhances heat storage within urban regions.

Table 5: Land Cover Distribution of Pakistan (2019

Land Cover Class	Percentage (%)	Area (km²)
Built-up	0.50	4,409.57
Agricultural Land	25.00	220,478.25
Dense Vegetation	10.86	95,775.75
Sparse Vegetation	3.00	26,457.39
Barren Land	26.00	229,297.38
Shrub Land	31.68	279,390.04
Water	0.73	6,437.96
Snow/Ice	2.24	19,754.85

3.1.2 Land Surface Temperature Mapping

In 2019, the Land Surface Temperature (LST) distribution clearly reflects the impact of extensive land use/land cover transformation across Pakistan's climatic zones.

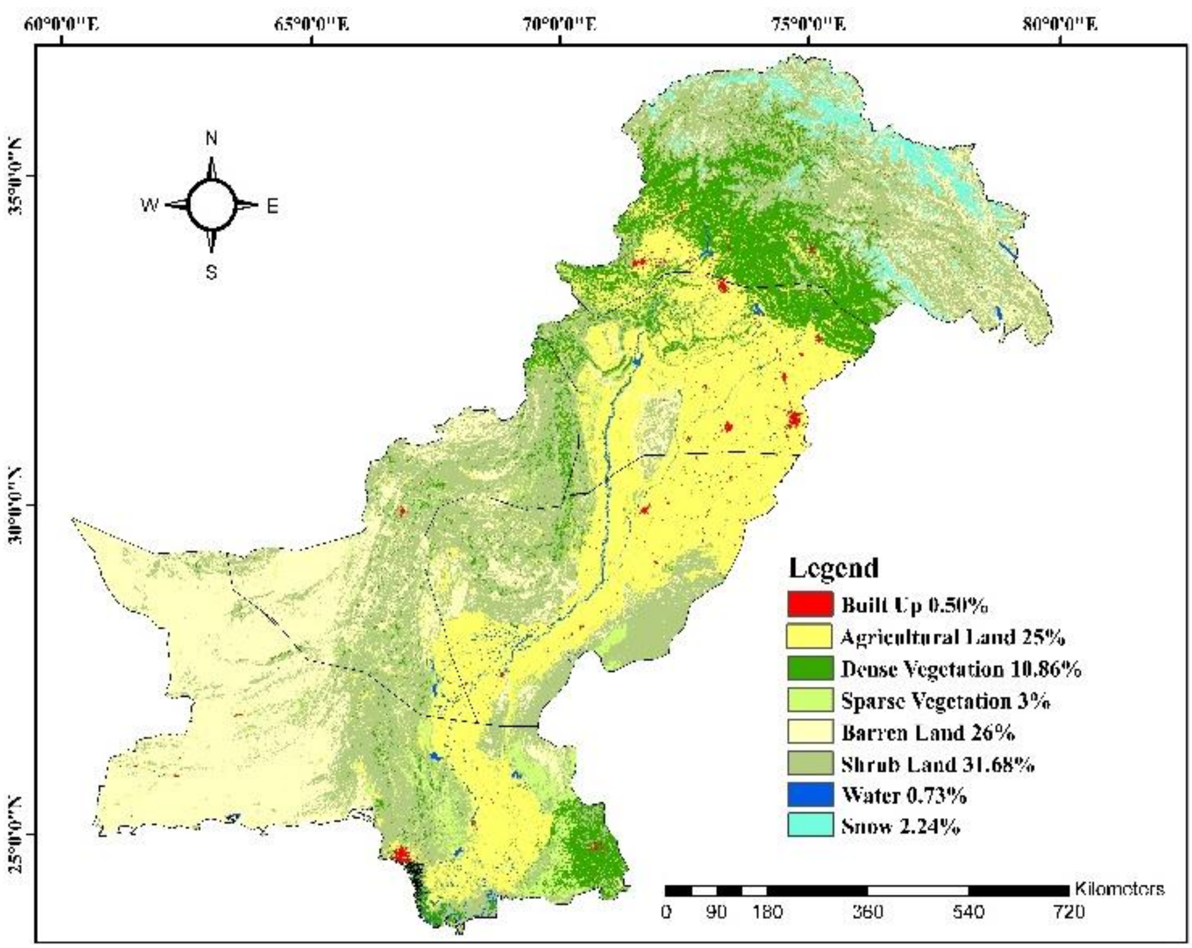

Fig. 3 Land Use Land Cover of Pakistan 2019 showing the spatial distribution of major land cover classes.

Natural landscapes such as dense vegetation, agricultural land, and barren land have been largely transformed into urban areas characterized by impermeable surfaces including roads, pavements, and buildings, which significantly increase surface temperature. Impervious urban materials possess high heat absorption and low moisture retention capacity, resulting in greater daytime heating and slower nighttime cooling. The reduction in vegetation has led to decreased evapotranspiration, a key cooling process through which plants release water vapor to regulate the thermal environment. As a result, elevated temperatures are predominantly associated with urbanized regions. Figure 4 shows that LST values in 2019 ranged from approximately –26 °C in the high-altitude northern mountainous regions to about 50 °C in the southern and central plains. Zones B, C, D, and E experienced the highest temperature intensities, coinciding with rapid urban expansion and infrastructure development. The elevated temperatures in these zones may also be associated with increasing anthropogenic activities, population concentration, and reduced green cover, which collectively intensify thermal stress conditions. The extensive built-up surfaces absorb and re-radiate solar energy, thereby intensifying the Urban Heat Island effect in major cities within these climatic zones.

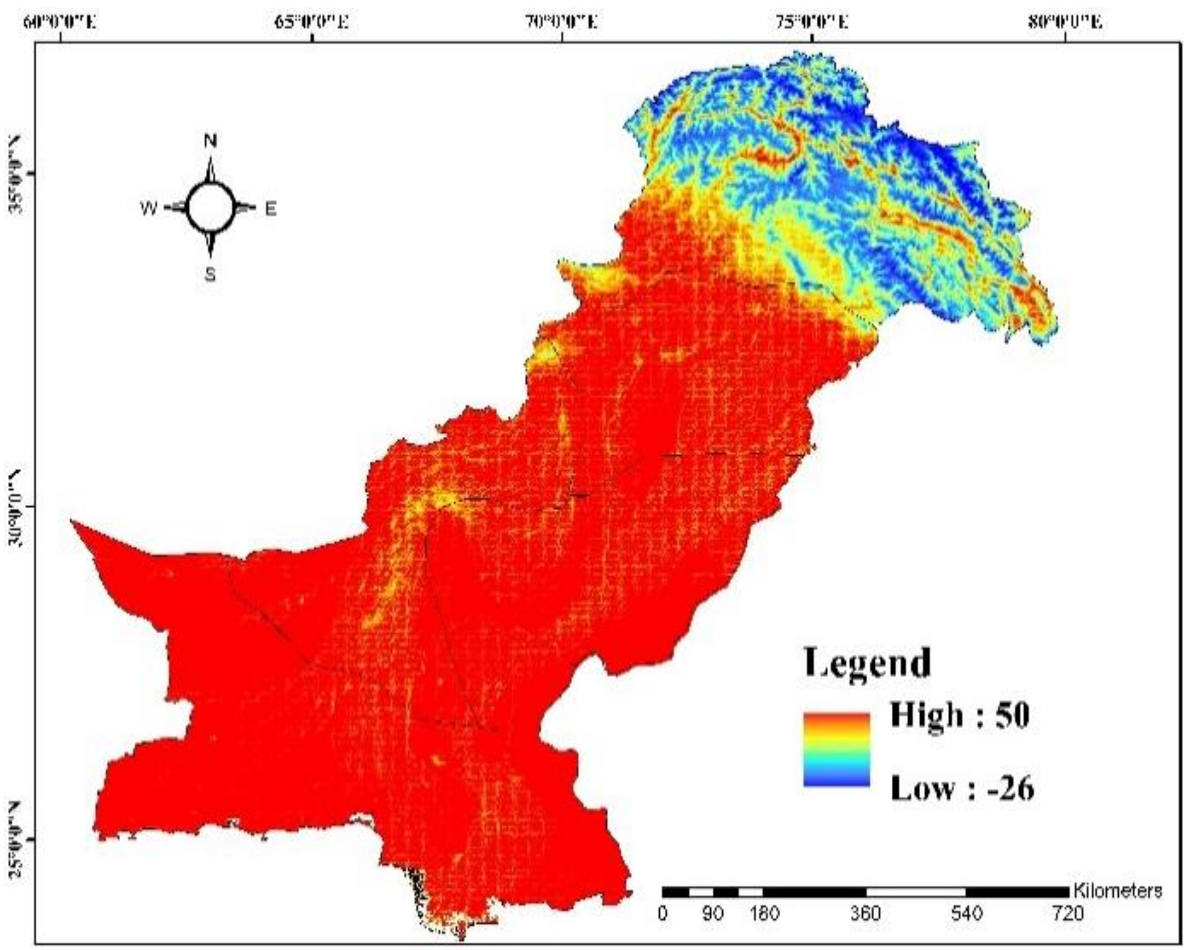

Fig. 4 Land Surface Temperature of Pakistan 2019 showing the spatial variation in surface temperature across the study area.

Table 6: Land Surface Temperature (LST) Distribution in Pakistan (2019).

Climatic Zone	Dominant LULC characteristics (2019)	Observed LST range (°C)	Temperature intensity	Remarks
Zone A	High mountain regions with permanent snow, glaciers, sparse alpine vegetation, and very limited human activity	–26 – 10	Low	Very low LST is controlled by high elevation, snow/ice cover, and strong radiative cooling in northern high-altitude regions.
Zone B	Sub-mountainous areas with mixed forest cover, rangelands, and scattered agriculture	35 – 50	High	High thermal conditions influenced by elevation gradient and partial vegetation cover
Zone C	Mountainous and intermontane valleys with mixed land use, seasonal agriculture, and fragmented vegetation	38 – 50	High	High variability due to elevation differences, seasonal heating, and mixed vegetation cover
Zone D	Arid and semi-arid plains with sparse vegetation and extensive bare soil (Thar, Cholistan, interior Sindh/Balochistan)	38 – 50	High	Highest LST due to extreme aridity, low moisture content, high solar insolation, and bare soil dominance
Zone E	Coastal plains including Sindh coastal belt and Makran coast with urban centers (e.g., Karachi) and mixed agricultural–barren land	30 – 42	Moderate to High	Moderate to High LST due to sea–land breeze circulation, coastal humidity, and mixed urban–vegetation land cover reducing extreme temperature peaks

3.1.3 Urban Heat Island Mapping

Urban Heat Island (UHI) analysis in this study is based on spatial variations in Land Surface Temperature (LST) and hotspot patterns within and around urban and peri-urban areas, which are the primary focus of UHI assessment. In 2019, a significant rise in Urban Heat Island (UHI) intensity is evident across Pakistan's major climatic zones, as illustrated in Figure 5. The UHI was classified into five categories, namely Cool Zones, Negligible Exposure, Significant Exposure, Strong Exposure, and Very Strong Exposure. The spatial distribution in 2019 shows that Zone C, Zone D, and Zone E are predominantly affected, exhibiting strong to very strong UHI exposure. These zones correspond to areas experiencing extensive land cover transformation, where urbanization has expanded at the expense of agricultural land, natural vegetation, and barren land. Such large-scale conversion of permeable and vegetated surfaces into impervious urban structures significantly alters surface energy balance and promotes localized heat retention. Zone E, characterized largely by arid and sparsely vegetated landscapes, shows widespread very strong UHI exposure, intensifying the heat stress conditions. The already dry climatic conditions in this zone further amplify thermal intensity due to limited vegetation-mediated cooling effects. Zone E represents the coastal and arid climatic region of Pakistan, including the Arabian Sea coastal belt and arid Sindh plains, as defined in the climatic zone classification (Qasim et al., 2014), and is not associated with mountainous terrain. Similarly, Zone D and Zone C display pronounced UHI hotspots, particularly around major urban centers and rapidly growing cities. This pattern indicates that rapid urban growth without proportional green infrastructure development may substantially increase urban thermal vulnerability. In contrast, Zone A remains largely within the cool to negligible exposure classes, reflecting lower urban density and the presence of natural and mountainous landscapes (Table 6). Mountainous terrain and higher vegetation density in Zone A likely contribute to lower surface temperatures through enhanced shading and evapotranspiration processes. Overall, the transition of agricultural and natural land covers into urban and impervious surfaces in 2019 has substantially contributed to elevated surface temperatures, resulting in intensified UHI exposure across Pakistan. The spatial distribution of UHI intensity in 2019 is described in Table 6.

In 2019, the Urban Heat Island (UHI) effect was most pronounced across built-up areas, reflecting the cumulative impact of land-use and land-cover changes. The trend line in Figure 6 indicates that built-up land recorded the highest surface temperature, reaching approximately 50°C, highlighting intense heat accumulation associated with urbanization and impervious surfaces. Barren land also exhibited elevated temperatures, peaking at around 48°C, while sparse vegetation showed relatively high thermal values near 34°C. In contrast, agricultural land and shrub land displayed moderate temperatures of about 39°C and 35°C, respectively, indicating transitional thermal behavior between urban and natural surfaces. Dense vegetation maintained the lowest surface temperature, approximately 27°C, demonstrating its significant cooling effect.

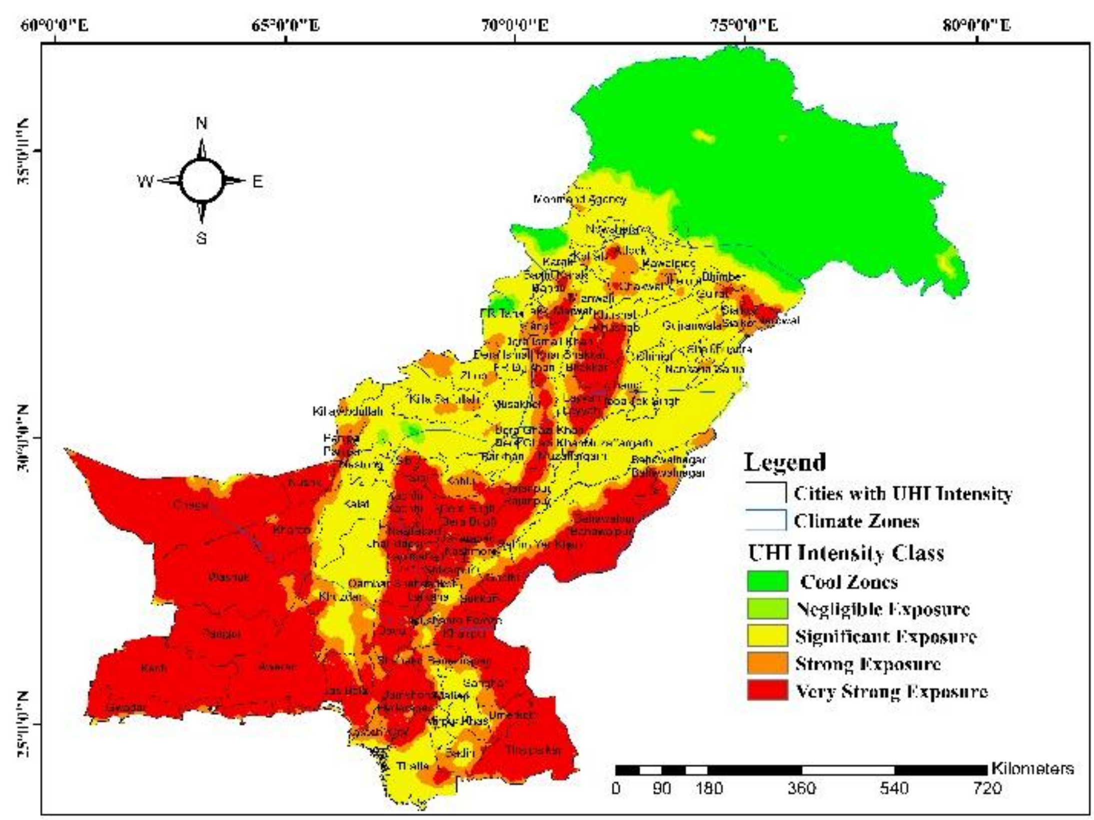

Fig. 5 Urban Heat Island (UHI) of Pakistan 2019 showing spatial distribution of UHI intensity across the study area.

Table 7: Spatial Distribution of Urban Heat Island (UHI) Intensity in 2019.

Climatic Zone	Dominant UHI Class (2019)	Description of UHI Condition
Zone A	Cool Zones to Negligible Exposure	Predominantly cool conditions with minimal UHI influence, reflecting higher elevation, lower urbanization, and greater vegetation cover.
Zone B	Significant to Strong Exposure	Mixed UHI intensity with noticeable hotspots around major urban centers and transportation corridors.
Zone C	Strong to Very Strong Exposure	Extensive UHI effects observed, driven by dense urban growth, agricultural land transformation, and reduced vegetation.
Zone D	Strong to Very Strong Exposure	Highly affected by UHI due to rapid urban expansion, increased impervious surfaces, and land cover modification.
Zone E	Very Strong Exposure	Dominated by extreme UHI conditions, largely associated with arid climate, barren land, sparse vegetation, and expanding urban settlements.

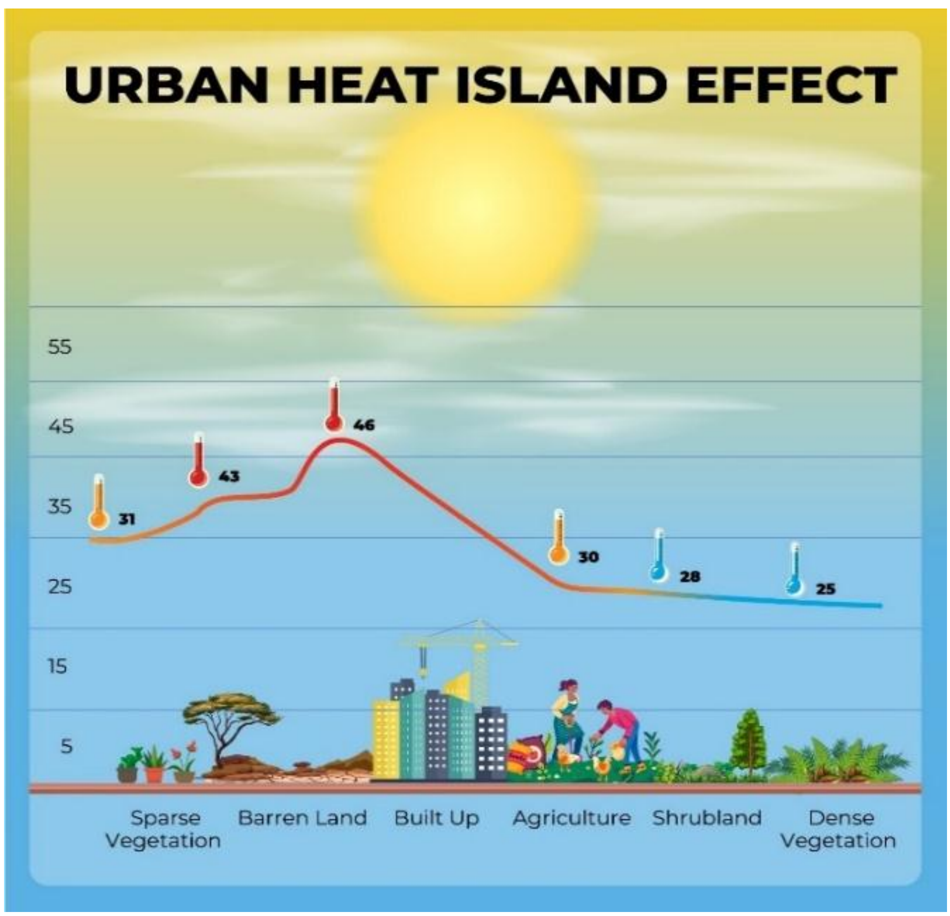

Fig. 6 Trend in Land Use and Land Cover (LULC) and Urban Heat Island (UHI) classes in 2019.

This cooling influence is primarily attributed to vegetation-driven evapotranspiration and shading effects, which help regulate surface thermal conditions. These 2019 observations clearly illustrate the inverse relationship between vegetation cover and surface temperature and emphasize the critical role of green spaces in mitigating UHI intensity under rapidly expanding urban conditions.

3.2. *Bibliometric analysis of UGS and LST*

The bibliometric analysis of UGS and LST research from 2006 to 2021 is organized into four sections: current research status, keyword co-occurrence analysis, co-authorship analysis, and co-citation analysis. The results are presented as follows;

3.2.1 Current Status of UGS and LST Study (Discussion of findings)

In this context, the spatio-temporal distribution of UGS and LST-related publications was analyzed in terms of countries, organizations, journals, authors, and H-index.

3.2.1.1 Spatio-temporal distribution of related publications

The spatio-temporal distribution (Fig. 7) indicates slow research productivity during 2006–2011, followed by a steady increase after 2013 and rapid growth in recent years. A strong upward trend was observed ($R^2 = 0.7861$), reflecting increasing research productivity and collaboration in the UGS and LST domain (Liu et al., 2019; Akhtar et al., 2019). Research productivity for 2016–2021 is illustrated in Figure 8.

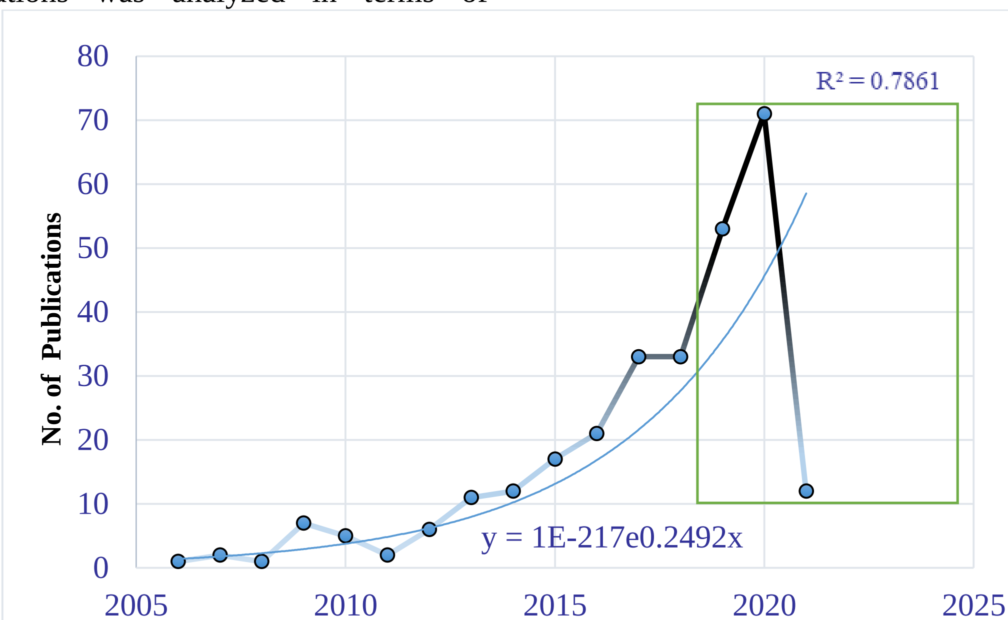

Fig. 7 Spatio-temporal distribution of UGS and LST research studies (2006-2021)

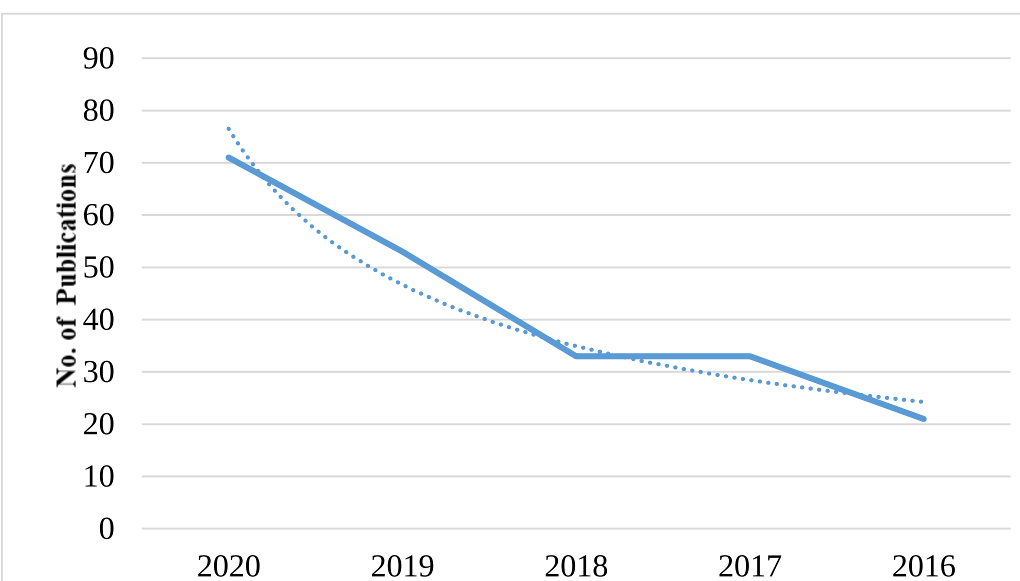

Fig. 8 Five-Year Annual Productivity in UGS and LST.

3.2.1.2 The Geographical distribution of UGS and LST research productivity

UGS and LST research has expanded across 55 countries (Figure 9), with China (91), India (82), and the USA (36) as the leading contributors, followed by Iran, Malaysia, Australia, Nigeria, Pakistan, and South Africa. A total of 407 organizations contributed to this field, led by the Chinese Academy of Sciences with 43 publications (14.98%), followed by the University of the Chinese Academy of Sciences (11), Federal University of Technology Akure (9), Universiti Putra Malaysia (9), and several other institutions (Figure 10). The 287 publications were distributed across 129 journals, with *Remote Sensing* ranking first. Most journals published fewer than two papers, while 31.1% of publications were concentrated in the top ten journals. The leading journals are presented in Figure 11.

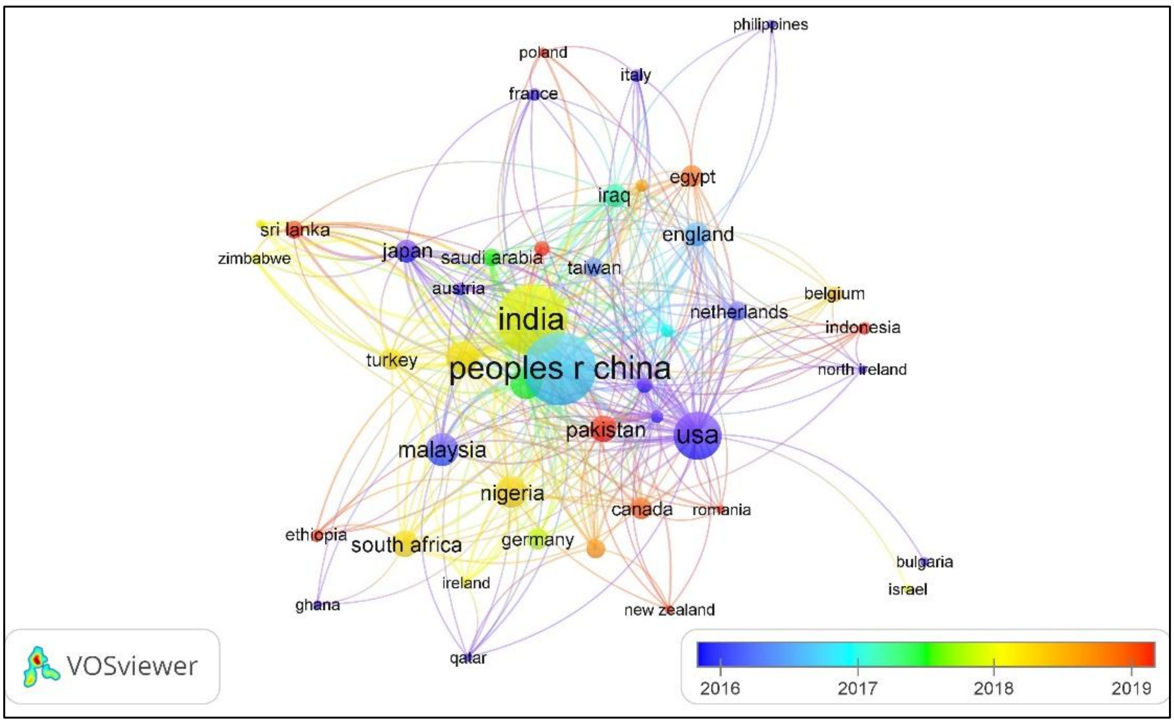

Fig. 9 Geographical Network of UGS and LST Research Productivity.

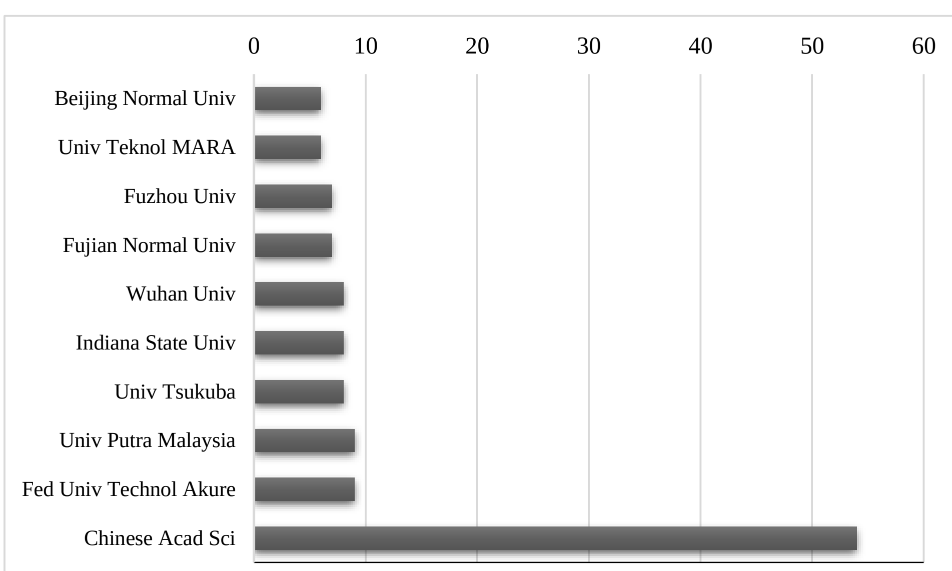

Fig. 10 The Top 10 Organizations with UGS and LST-related Publications

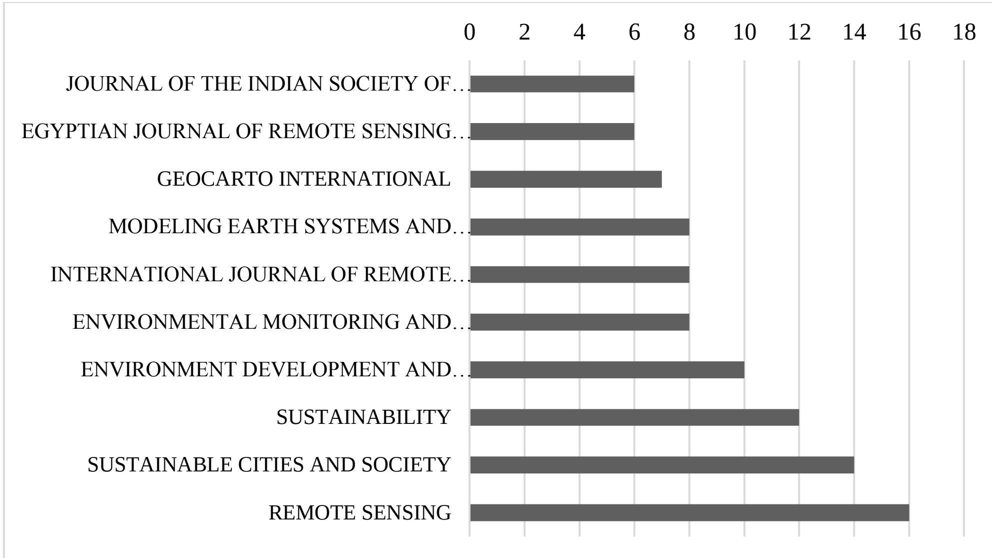

Fig. 11 The Top 10 Journals with UGS and LST-related Publications.

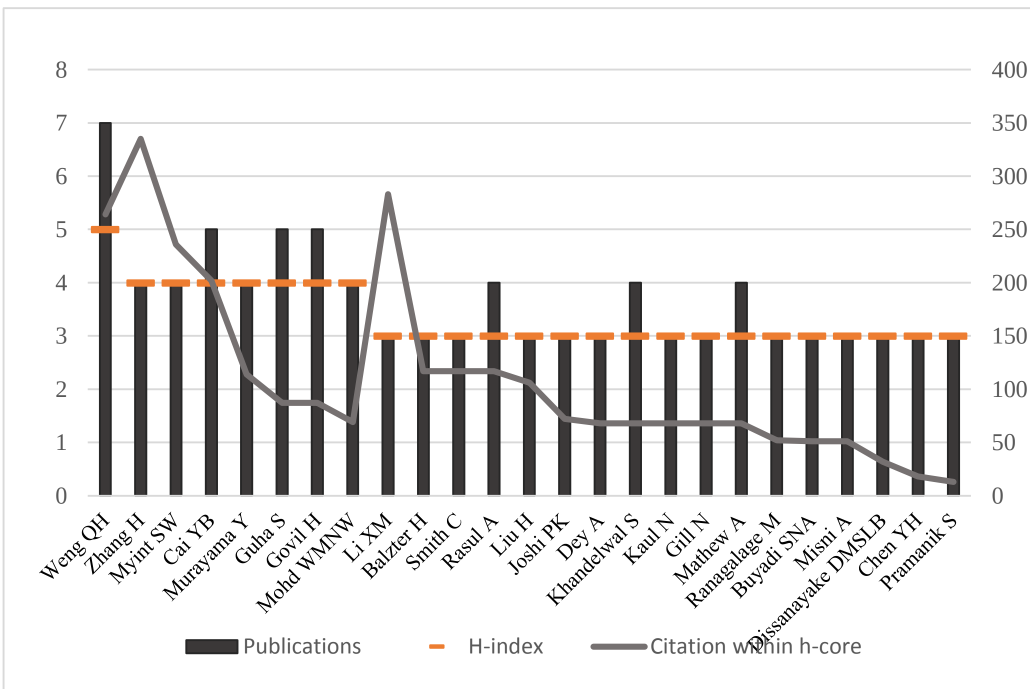

Fig. 12 Top Twenty-Five Authors based on No. of Publications and H-Index.

Top twenty-five most productive authors on Urban Green Spaces (UGS) and Land Surface Temperature (LST) from 2006 to February 2021 were identified using BibExcel, with author names standardized and analyzed through Pivot Tables in Excel. The H-index, introduced by Hirsch (2005), was used to assess scientific impact and citation performance, reflecting both productivity and influence (Bertoli-Barssotti & Lando, 2017; Bounoua & Daniel, 2007; Díaz et al., 2016). The results are presented in Figure 12.

3.2.2. *Keyword Co-occurrence Analysis*

Keyword co-occurrence analysis was performed to examine relationships and research hotspots in UGS and LST studies (Picone et al., 2021; Li et al., 2016). From 287 publications, 1000 keywords were identified, of which 121 keywords with at least five occurrences were retained for analysis. The VOSviewer-based co-occurrence map is presented in Figure 13, where node size represents keyword frequency and links indicate co-occurrence strength (Gu et al., 2017). Eight clusters were identified, with “land surface temperature” (105), urbanization (79), urban heat island (61), and city (59) as the most frequent keywords.

3.2.3. Co-authorship Analysis

Co-authorship analysis is an important aspect of bibliometric studies that helps identify research collaboration patterns in a specific field (Reyes – Gonzalez et al., 2016; Pinto et al., 2014). In this study, WoS publications were analyzed to examine collaboration among countries, organizations, and authors, along with highly cited UGS and LST studies.

3.2.3.1 Country Co-Authorship Analysis

The country co-authorship network (Fig. 14) shows collaboration intensity through node size, link strength, and distance. China is the leading research hub with the highest link strength (58), followed by the USA (36) and India (23). The analysis further shows differences between citation impact and collaboration strength, indicating that geographical presence does not necessarily determine research cooperation levels.

3.2.3.2 Institute Co-Authorship Analysis

The institute co-authorship network (Fig. 15) shows the Chinese Academy of Sciences, Federal University of Technology Akure, and Universiti Putra Malaysia as the leading institutions in UGS and LST research, with strong collaboration from major Chinese universities such as Wuhan University, Fujian Normal University, Fuzhou University, and Beijing Normal University.

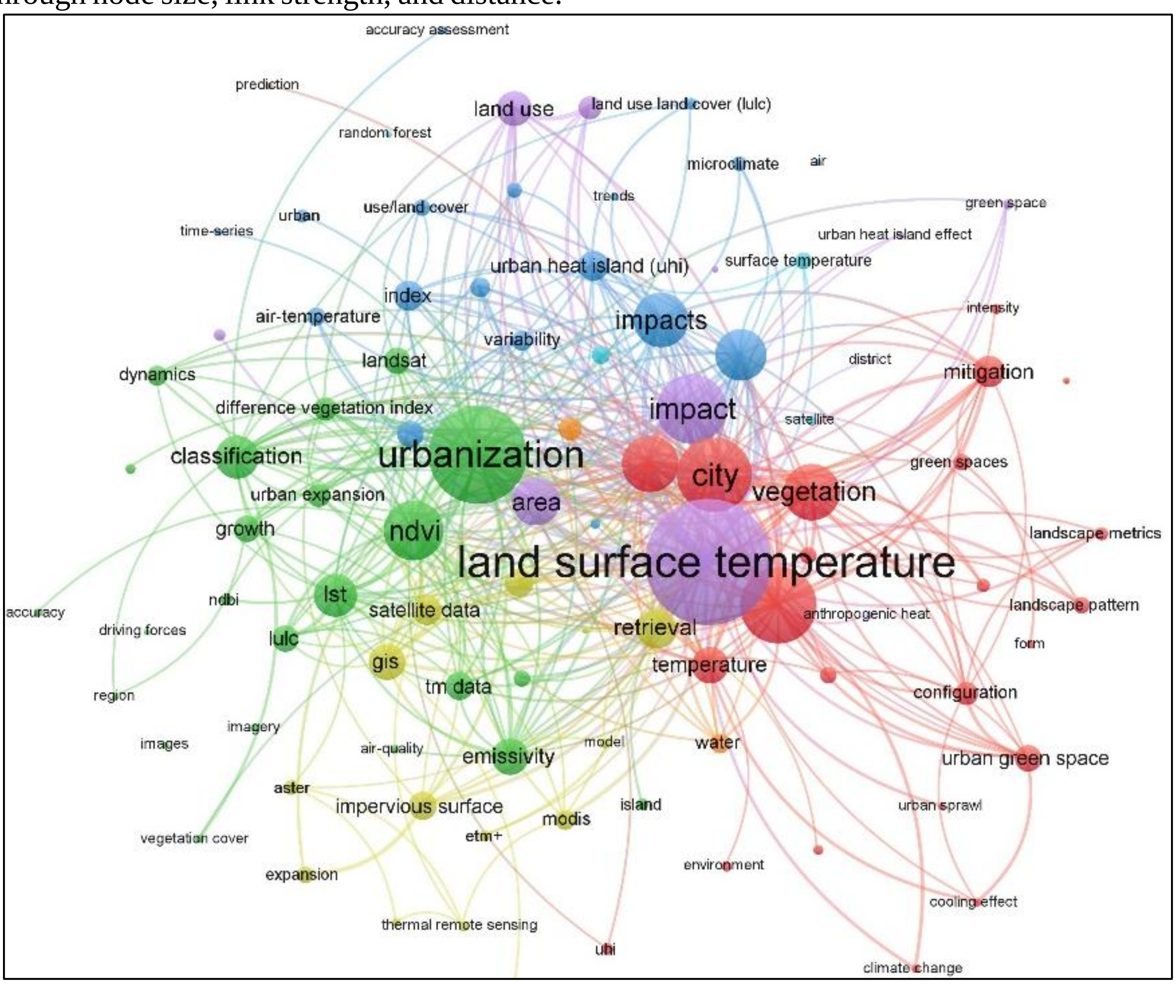

Fig. 23 Keyword Co-occurrence Network of UGS and LST-related Publications.

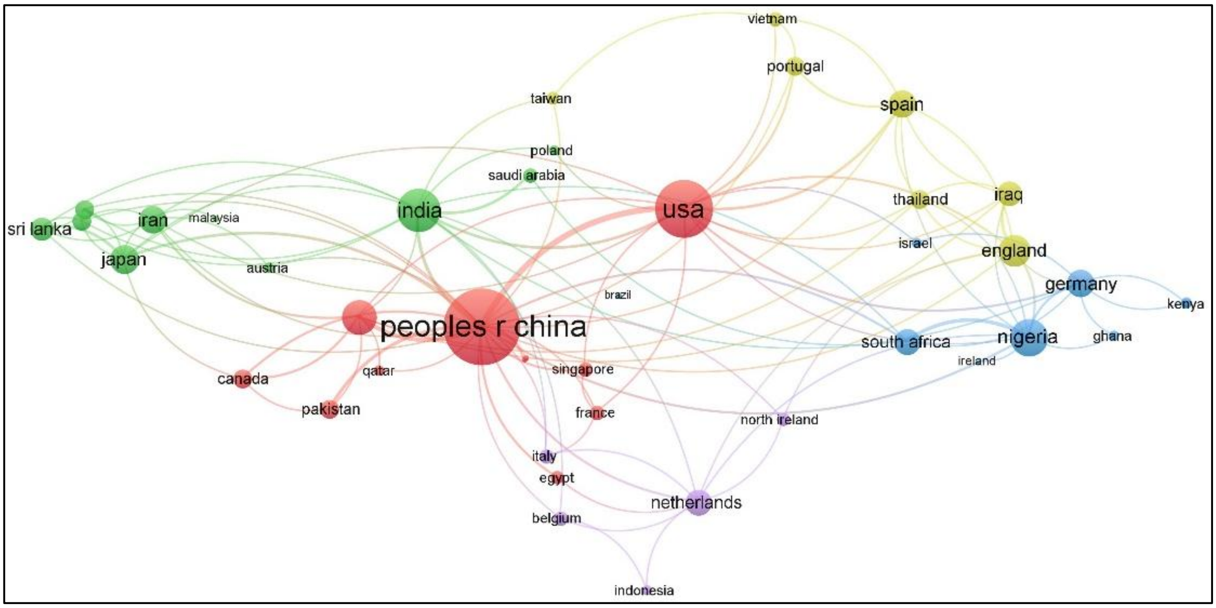

Fig. 34 Country Co-Authorship Network of UGS and LST-related Research.

3.2.3.3 Authors Co-Authorship Analysis

The author co-authorship map (Fig. 16) reveals six collaboration clusters (Table 7), highlighting strong author collaboration and the need to further strengthen international research partnerships.

Table 8: Co-authorship Cluster Details with affiliation and research area.

Cluster Name	**Scholars Affiliations**	**Research Area**
Cluster 1	Nazrul Balika Vidyalaya: West Bengal, India National Institute of Technology, Raipur, India] All India Institute of Medical Sciences, Raipur, India	Applications of remote sensing in geography and urban land use.
Cluster 2	University of Leicester, UK Soran University, Iraq	Earth Observation and models for ecosystem services
Cluster 3	Fuzhou University, China Fujian Normal University, China Fudon University, China	GIS/RS
Cluster 4	Malaviya National Institute of Technology Jaipur, India National Institute of Technology, Tiruchirappalli, India	Environmental Engineering Remote sensing /GIS application
Cluster 5	Rajarata University of Sri Lanka University of Tsukuba, Japan	GIS & Remote sensing, urban development, transport geography and agricultural research
Cluster 6	Old Dominion University, USA Indiana State University, USA	Urban environmental change, climate change, Remote sensing, GIS

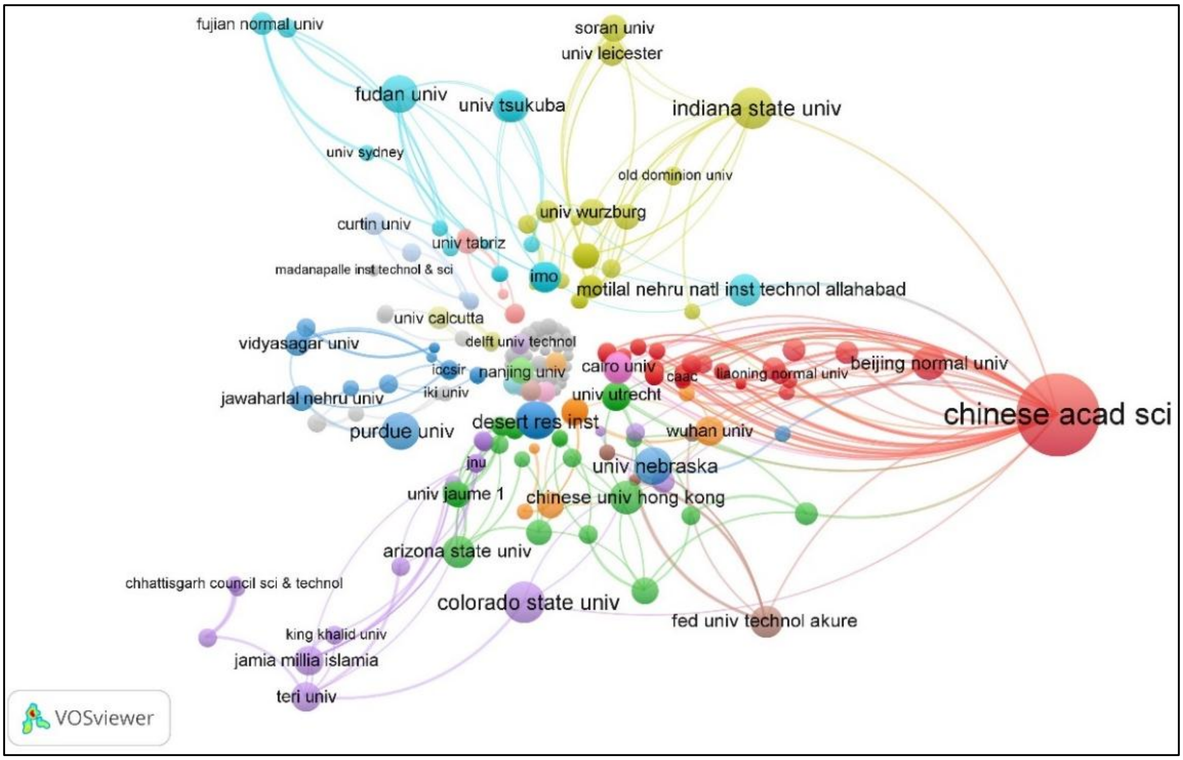

Fig. 45 Institute Co-Authorship Network of UGS and LST-related Research.

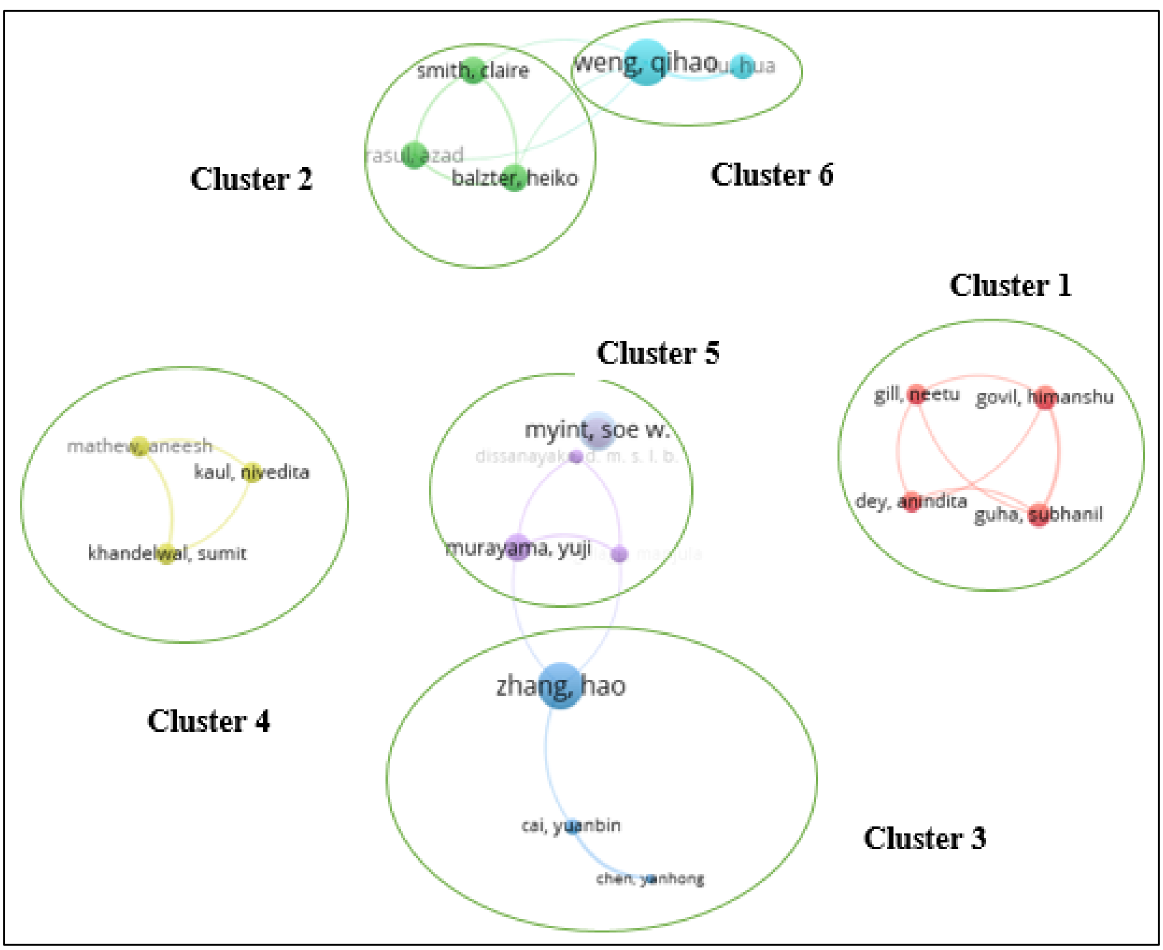

Fig. 56 Co-Authorship network with six clusters working on UGS and LST-related research.

3.3. Co-Citation Analysis

Co-citation refers to the simultaneous citation of two items (authors, journals, or documents) in the reference list of a third citing work (Osareh, 1996). Since its introduction by Small (1973), it has been widely used to examine relationships and structure within scientific literature (Weinberg, 1974; Boyack and Klavans, 2010). In co-citation networks, nodes represent the strength of thematic relationships between research outputs. In this study, co-citation analysis (Fig. 17) indicates that Weng qh, Voogt ja, and Oke tr are the most influential contributors in UGS and LST research.

4. Discussion and Conclusion

The 2019 Urban Heat Island (UHI) map (Fig. 5) reveals a clear intensification of surface heating across Pakistan's major climatic zones, particularly Zones B, C, D, and E, while Zone A largely remains within cool to negligible UHI conditions. These spatial patterns strongly reflect the extent of urbanization, vegetation loss, and land cover transformation. In Zone B, strong to very strong UHI exposure in cities such as Lahore, Faisalabad, Multan, Rawalpindi, and Islamabad corresponds with extensive urban expansion and reduced green cover. Previous studies report surface temperature increases of approximately 2–2.4°C in these cities, confirming a strong positive relationship between built-up area growth, increased LST, and UHI intensity (Saleem et al., 2020; Mehmood et al., 2022; Arshad et al., 2024; Nasar-u-Minallah et al., 2024). Similar urban-driven warming trends have been documented for the twin cities, where rapid infrastructure development has contributed to rising minimum and maximum temperatures (Sajjad and Blond, 2020).

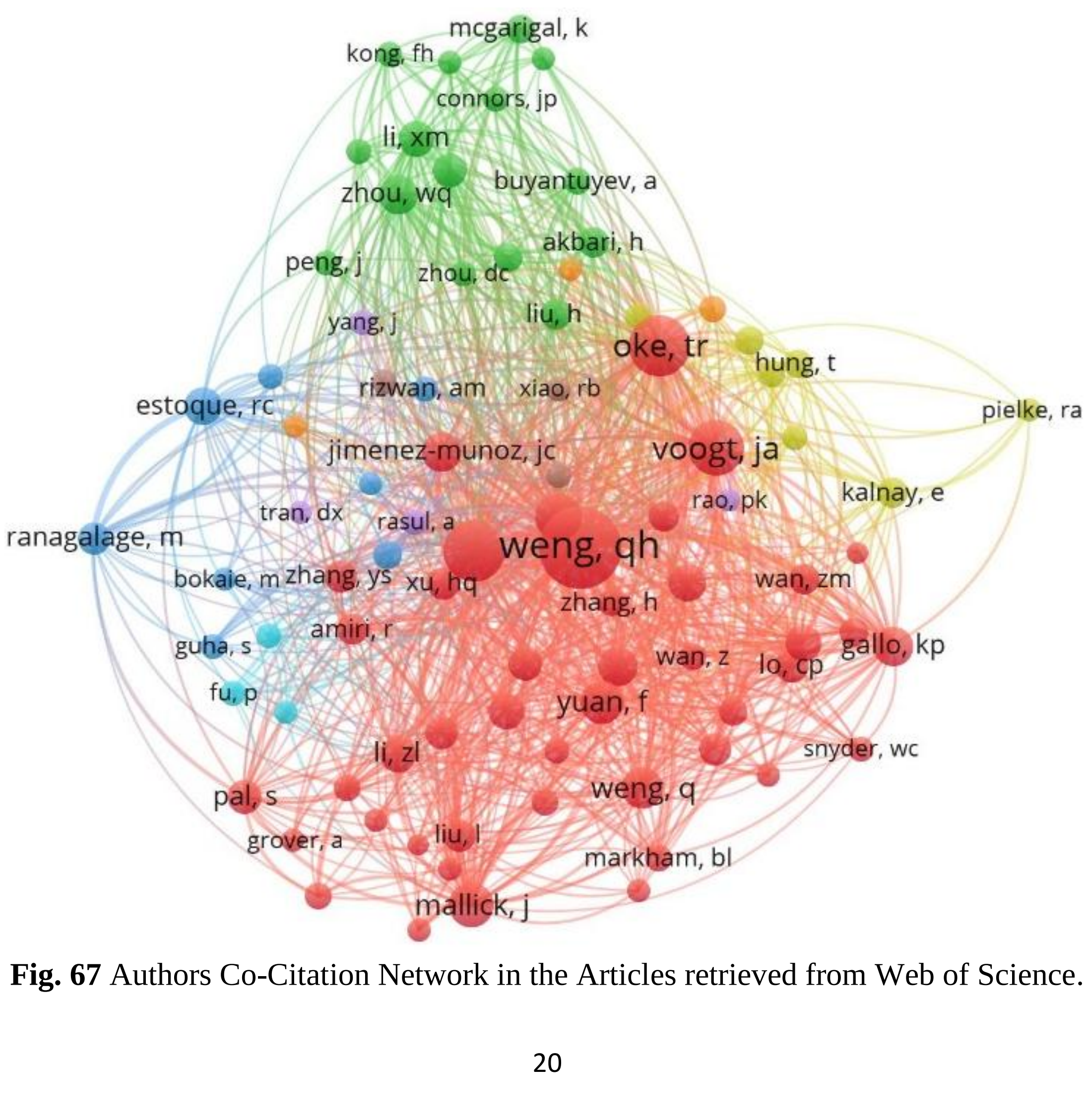

Fig. 67 Authors Co-Citation Network in the Articles retrieved from Web of Science.

These stronger UHI intensities in densely urbanized climatic zones can be attributed to higher impervious surface fraction, reduced evapotranspiration, and enhanced heat storage capacity of built-up materials (Mehmood et al., 2022; Arshad et al., 2024). Zone C, covering much of Baluchistan, exhibits pronounced UHI intensity in 2019, particularly in Quetta and Khuzdar. The elevated LST in this zone is attributed to arid climatic conditions, high solar radiation, increasing urbanization, and pollution, consistent with earlier findings (Anjum et al., 2017; Abbas et al., 2018; Sajjad and Blond, 2020). Comparable warming trends in neighboring regions further support the role of regional climate and land cover changes (Tabari and Talaee, 2011). The absence of dense vegetation in this arid zone further amplifies surface heating due to reduced shading and soil moisture availability (Anjum et al., 2017). In Zone D, characterized by extreme heat and aridity, very strong UHI exposure is evident in 2019. Cities such as Multan, Bahawalpur, Sukkur, and Hyderabad show elevated surface temperatures driven by urban expansion, declining agricultural land, and the dominance of barren and built-up surfaces (Qasim et al., 2014; Saleem et al., 2020; Kalwar et al., 2022; Mohsin, 2015). This indicates a strong conversion of vegetated/agricultural land into impervious surfaces, directly contributing to higher LST values (Qasim et al., 2014; Saleem et al., 2020). Zone E, particularly Karachi, shows intense UHI conditions in 2019 due to rapid urban growth and increasing impervious surfaces. **T**his observation is consistent with the classification of Zone E as a coastal–arid climatic region influenced by the Arabian Sea and arid Sindh plains, rather than mountainous characteristics, ensuring alignment with the defined climatic zones. Although short-term NDVI improvements were observed following heavy rainfall, built-up expansion remains the dominant driver of UHI formation (Lakhan et al., 2023; Ejaz et al., 2025). In contrast, localized vegetation increases in Hyderabad demonstrate the cooling role of agricultural land (Soomro et al., 2023). This highlights the buffering effect of vegetation through evapotranspiration, which helps regulate surface temperature in urban environments. Zone A exhibits minimal UHI effects in 2019 due to high elevation, dense vegetation, and limited urban development. However, emerging warming near tourist centers suggests early-stage UHI development, highlighting the need for sustainable land management in these sensitive regions (Khan et al., 2024).

Zone B exhibits strong UHI due to high-density impervious surfaces in major urban centers (Lahore, Faisalabad) with limited green space coverage, resulting in reduced evapotranspiration and increased sensible heat flux (Arsalan, 2025; Baqa et al., 2022). Zone D shows high UHI due to the combination of arid climate (high solar radiation absorption by barren surfaces) and sparse vegetation offering minimal evaporative cooling (Gourfi et al., 2022). Zone E’s UHI is intensified by industrial heat emissions and waste heat from concentrated infrastructure; this further reflects its coastal urban-industrial setting (Hamdi et al., 2025; Ullah et al., 2025). Zone A maintains lower UHI due to higher vegetation cover and lower urban density. Zone A shows minimal UHI due to high altitude, snow cover (high albedo), and dense alpine vegetation providing active evaporative cooling. (Satti et al., 2023). Quantitative analysis shows each 0.1unit increase in NDVI reduces LST by approximately 1.84°C, demonstrating the significant cooling effect of vegetation at the national scale (Xiang et al., 2023).

Overall, the 2019 results confirm that intensified urbanization, vegetation loss, and land cover transformation are the primary drivers of UHI across Pakistan’s urban regions. These findings emphasize the necessity of integrating green infrastructure and climate-sensitive urban planning to mitigate future UHI impacts. As the studies reveal that UGS and LST have an inverse relationship leading towards the generation of UHI; however, their causes and effects are adverse (affecting public health and biodiversity globally, regionally, and at the local level) and are compelling researchers, policy makers, even public to strive for ecological and environmental sustainability. Firstly, considerable research has been conducted on the UGS and LST relationship, confirming the cooling effect of UGS and its role in mitigating UHI. Research productivity was low initially (1–2 publications/year), increased gradually in 2009–2010 (5–7/year), and accelerated after 2013 (11 to 73 publications by 2020), with 12 publications in early 2021. Major productivity was observed since 2016. Three journals contributed 14.6% of publications, while China, India, and the USA were leading contributors. The Chinese Academy of Sciences alone contributed 18.8% (54 publications). Secondly, keyword analysis shows LST is strongly linked with urbanization and cities, while vegetation-related terms (NDVI, classification, mitigation) indicate key strategies for reducing UHI. Thirdly, strong collaboration exists among countries and institutions, though international cooperation needs improvement (Iglič et al., 2017). Co-authorship networks (Figures 9, 10 & 11) show China as the leading hub, with collaboration clusters across China, USA, India, UK, Sri Lanka, and Japan. Fourthly, co-citation analysis (Fig. 12) identifies Weng QH as the most influential author, followed by Sobrino JA and Oke TR in UGS–LST–UHI research.

This study is limited by the use of a single-year dataset, which may not capture temporal variability. Potential uncertainties in LST retrieval. Overall, urban expansion, vegetation loss, and land cover change drive UHI in Pakistan (2019), with Zones B–E strongly affected. UGS reduces LST and mitigates UHI, while global bibliometric trends (2006–2021) show increasing research but limited collaboration. These findings highlight the need for green infrastructure, sustainable planning, and long-term monitoring for UHI mitigation.

Authors' Contribution

Aneeza Islam proposed the main concept of the study, conducted the research, performed data analysis, prepared the figures, and wrote the original manuscript. Syeda Maria Ali supervised the research, provided scientific guidance, reviewed the methodology, and critically reviewed and proofread the manuscript. Iftikhar Ali assisted in the research design, provided technical guidance, and reviewed the manuscript. Sidra Aman Rana provided relevant literature support and reviewed the manuscript. Sami Ullah provided the data used in this study and contributed to data acquisition. Syed Adnan contributed to the technical review of the manuscript, provided valuable suggestions before submission, and proofread the final version. All authors read and approved the final manuscript.

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Statement and Declaration

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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