Spatial Patterns of Urban Heat Islands and Green Space Cooling Effects in the Urban Microclimate of Karachi

Aly Muhammad Gajani [1 *]

[1] Institute of Space Science and Technology, University of Karachi, Karachi, Pakistan, 75270
[*] Corresponding author: alygajani@gmail.com

Abstract

With rapid urbanization and the increasing threats of climate change, metropolitan cities like Karachi, Pakistan, are encountering greater challenges due to the Urban Heat Island (UHI) phenomenon. Understanding the cooling potential of urban green spaces (UGS) is crucial for mitigating heat stress and enhancing urban resilience. This study aims to analyze the thermal dynamics and cooling efficacy of UGS within Karachi's urban centre through a comprehensive analysis of UHI intensity and the delineation of thermal hot and cool spots in relation to the city's landscape. The analysis reveals a strong positive correlation between the cooling intensity of parks and their buffer distance in all four UGS studied (Karachi golf club, Clifton urban forest, UoK green space, and Safari park), with an average cooling distance of 250 meters. It was found that Karachi West and Malir districts displayed the strongest UHI effects and higher levels of thermal discomfort. Hotspot analysis further confirmed this relationship, revealing a prevalence of cold spots near coastal areas and hotspots in districts lacking green spaces. The study highlights the significance of giving priority to the development and preservation of green spaces, especially in identified hotspots, to enhance the livability of Karachi and create a cooler environment.

Keywords: Urban green space; Urban Heat Island; Land Surface Temperature; Hotspot analysis; UTFVI

1 Introduction:

As the impact of climate change and rapid urbanization continues to increase, cities worldwide are facing a significant challenge in managing rising temperatures and their adverse effects on public health, infrastructure, and ecosystems. According to the United Nations, more than half of the world's population currently lives in urban areas, and this percentage is expected to increase to 68% by 2050 (UN DESA, 2018).

The rapid growth of cities leads to something called the Urban Heat Island effect, especially in densely populated areas. The Urban Heat Island effect happens when cities become warmer than the surrounding rural areas (Oke, 1982; Rizvi et al., 2020; L. Yang et al., 2016). This occurs mainly because urban areas have more structures that absorb heat and fewer green spaces to cool things down. As a result, cities can have much higher temperatures than nearby countryside regions, especially during hot weather.

A recent report published by the Joint Research Centre has revealed that surface temperatures in cities can be up to 10-15°C higher than those in nearby rural areas (Mentaschi et al., 2022). Therefore, it is crucial to tackle the Urban Heat Island effect in heavily populated cities. If this phenomenon is left unattended, it can lead to increased energy consumption, a rise in heat-related illnesses, and elevated levels of air pollution (O'Malley et al., 2014; Xu et al., 2017).

Studies have revealed that the existence of green spaces such as urban parks and roadside greenways can significantly reduce surface temperatures and the overall temperature of cities (Aram et al., 2019; Chen et al., 2014; P. Yang et al., 2016; Yao et al., 2022). This is because they provide shade and evapotranspiration forming a 'park cool island' (PCI) (Jauregui, 1990). Trees and plants in these areas offer shade by blocking direct sunlight, while evapotranspiration cools the air and surfaces nearby by releasing water vapour. This combination effectively reduces temperatures within parks and their surroundings, helping to mitigate the urban heat island effect and regulate the urban microclimate. By examining the thermal dynamics and cooling capabilities of urban green spaces within an urban environment, we can uncover valuable insights into how these spaces can effectively mitigate the challenges presented by excessive urban heat.

The advancement of thermal infrared remote sensing technology has revolutionized urban climate studies by providing temperature data (Weng, 2009; Weng and Quattrochi, 2006). One crucial parameter derived from this technology is the land surface temperature (LST), which measures the direct temperature of the Earth's surface. LST is further used in various thermal comfort indices to quantify the spatial distribution of urban heat. One of the widely studied indexes is the Urban Thermal field Variance Index (UTFVI) which quantitively describes the intensity of the UHI effect. It offers insights into the fluctuation of temperature levels across urban landscapes, revealing areas where heat accumulates and disperses.

Multiple studies have shown that urban green spaces have a cooling effect and can help mitigate the urban heat island (UHI) phenomenon. These studies analyze the land surface temperature (LST), land cover changes and vegetation indices (Cao et al., 2010; Hassan et al., 2021; Lin et al., 2015a; Mackey et al., 2012; Yao et al., 2022). Research by (Nor et al., 2015), for instance, utilized LST data and the Park Cool Island (PCI) concept to evaluate the cooling intensity and spatial extent of parks in Malaysia’s Petaling district. Others employed statistical methods to map out areas having the hottest and coldest temperature clusters in the study area (Georgiana et al., 2018; Goswami et al., 2013; Ko and Cho, 2020; Mavrakou et al., 2018; Wang and Chang, 2020; Zargari et al., 2024). However, there is a lack of research on the extent of park cooling effects and their correlation with specific park characteristics in arid climates like Karachi, Pakistan, a city experiencing rapid urbanization and intensifying heat stress.

Research by (Sajjad et al., 2015) utilized the Finite Volume Mesoscale Model (FVM) to simulate urban heat island formation in Karachi. Their simulations, conducted over three days, revealed significantly higher temperatures within the urban core, ranging from 55.6°C to 13.5°C warmer compared to surrounding rural areas. Further exploring the link between urbanization and UHI in Karachi, Rizvi et al., (2020) explored the effects of Surface Urban Heat Island (SUHI). Their research concluded that the change in Land Use Land cover (LULC) due to rapid urbanization is the fundamental factor in LST variations. Their findings revealed a significant increase of 1.77 °C in daytime LST and 0.25 °C in nighttime LST, contributing to nocturnal UHIs.

The health consequences of UHI are not to be overlooked. Research on heat-health vulnerability by Wu et al., (2022) demonstrates that areas with high UHI intensity are more susceptible to heatwaves. This increased heat exposure can lead to adverse health effects for residents, highlighting the importance of identifying vulnerable populations living in high building density and low vegetation cover areas for targeted interventions.

Therefore, identifying and mapping areas experiencing high heat stress is crucial for planning and implementing urban green spaces. By strategically placing green infrastructure in areas most affected by heat stress, cities can create cooler microclimates, improve public health outcomes, and enhance the overall livability of the urban environment.

This study aims to conduct a comprehensive analysis of thermal dynamics in relation to the distribution of urban green spaces in Karachi. Thus, the objectives of this paper are (i) determining the relationship between park cooling intensity and buffer distances from selected parks, (ii) analyzing the spatial distribution of thermal comfort using the Urban Thermal Field Variance Index (UTFVI), and (iii) identifying thermal hotspots and coldspots through Getis-Ord Gi* statistics to inform future park planning efforts.

2 Material and Methods

2.1 Study Area

Karachi, the largest city in Pakistan, is situated on the southern coast and is surrounded by the Arabian Sea. It plays a vital role as an economic and industrial hub, accounting for about 25% of the country's GDP (Arifeen, 2016). The city is divided into seven districts and 31 sub-divisions, and its landscape features a coastal plain with rocky outcroppings, hills, and marshlands. Karachi has a hot desert climate (BWh) according to the Köppen classification. The summers are extremely hot, with average maximum temperatures of 34°C, while the winters are mild, ranging from 10°C to 25°C. The city receives minimal rainfall, averaging around 10 inches annually, mostly during the brief monsoon season from July to September. According to the recent census report of 2017, the population of the city surged to over 15 million, resulting in a high population density of 4,543 people per square kilometre within its expanse of 3,527 square kilometres (Statistics, 2017). Rapid urbanization has led to the dominance of 66% bare land and 21% built-up areas in the city's land cover, with only 10.4% designated as green spaces. This exacerbates the city's vulnerability to the urban heat island effect (Baqa et al., 2022). Concerns about heatwaves are also increasing, with studies documenting their growing frequency and intensity, posing significant threats to public health and well-being (Arshad et al., 2020a). This study aimed to analyze the cooling intensity of four urban green spaces: Karachi Golf Club, Clifton Urban Park, the University of Karachi's green space, and Safari Park. These spaces were chosen for their high tree density and popularity.

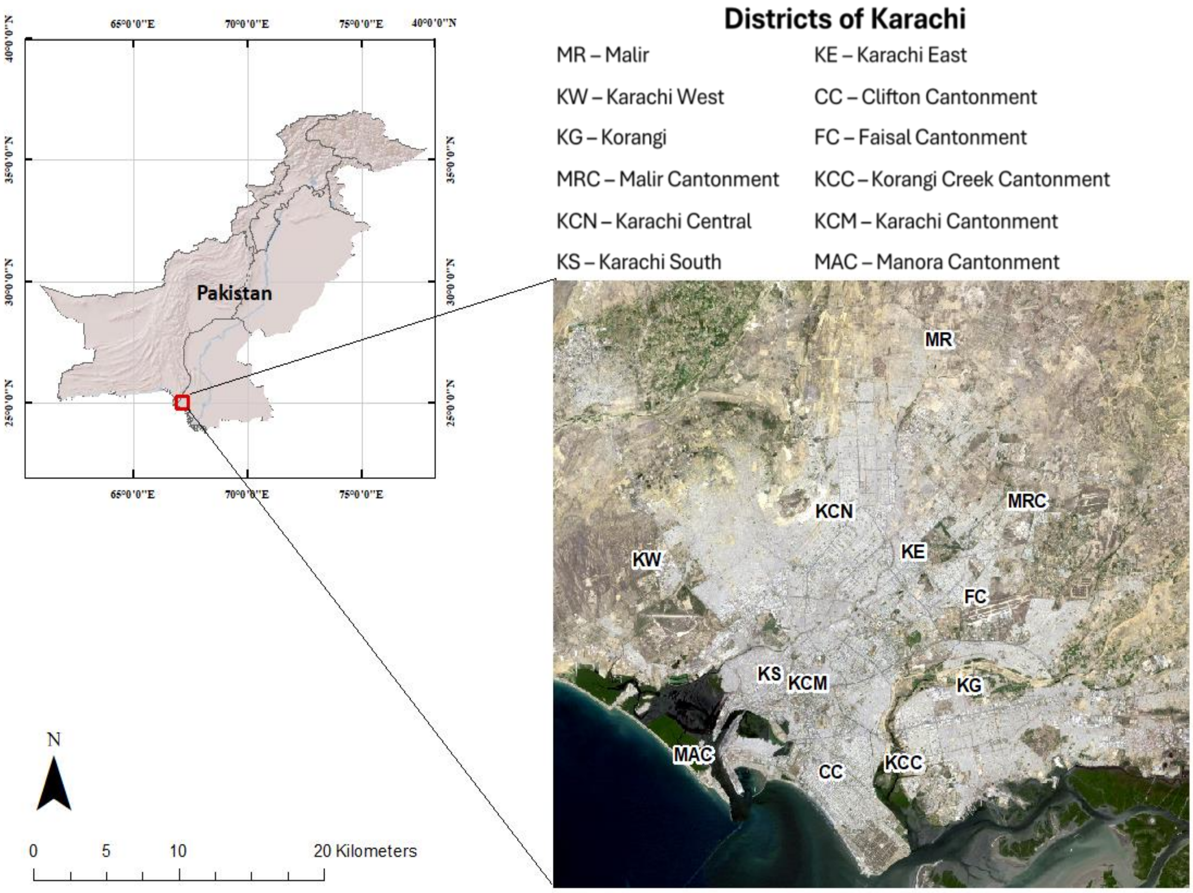

Fig 1 Map of the study area with names of districts.

2.2 Data Acquisition

To obtain the necessary data, we acquired Landsat 8 OLI/TIRS satellite images from the United States Geological Survey (USGS) Earth Explorer data website (http://earthexplorer.usgs.gov) for May 16, 2022, one of the hottest days in the year. Specifically, we focused on a tile having a path/row of 152/43, ensuring that the images had less than 10% cloud cover. These images were then used to calculate the land surface temperatures (LST) for both the Karachi urban area and the four chosen urban green spaces.

2.3 Retrieval of Land Surface Temperature (LST)

The data for LST was obtained from the thermal infrared sensor (TIRS) of the Landsat 8 satellite. There are many ways to compute the temperature from the thermal bands of Landsat satellites. One of the most popular and highly accurate methods is the radiative transfer equation method (RTE) (Ali et al., 2023; Berk et al., 1987).

The process includes calculating the spectral radiance and TIRS top of Atmosphere Brightness Temperature. We can convert the DN values from the thermal Band 10 to spectral radiance using eq. 1:

$$L_{\lambda i} = M_L * Q_{CAL} + A_L \qquad \textbf{(Eq. 1)}$$

Where

$L_{\lambda i}$ = TOA spectral radiance

M_L = Band-specific multiplicative rescaling factor

Q_{CAL} = Quantized standard pixel values (DN),

A_L = Band-specific additive rescaling factor

Now, the spectral radiance is utilized to convert the radiance into to effective at-satellite brightness temperature that can be expressed as :

$$BT = \frac{K_2}{\ln\left(\frac{K_1}{L\lambda i}+1\right)} - 273.15 \qquad \textbf{(Eq. 2)}$$

where K_1 and K_2 are the sensor-specific calibration constants provided in the metadata file of Landsat 8, having values 774.89 $W.m^{-2}.sr^{-1}\,\mu m^{-1}$ and 1,321.08 K respectively. When using the RTE to compute the LST the Land Surface Emissivity (LSE) is also required, which can be approximated using the NDVI-based emissivity estimation.

$$\varepsilon = 0.004Pv + 0.986 \qquad \textbf{(Eq. 3)}$$

The proportion of vegetation cover, Pv, can be expressed in the following way.

$$P_v = \left(\frac{NDVI = NDVI_{min}}{NDVI_{max} - NDVI_{min}}\right)^2 \qquad \textbf{(Eq. 4)}$$

The normalized Difference Vegetation Index (NDVI) is derived using the Near-infrared and red spectral band reflectance in Landsat images (Lillesand and Kiefer, 1979). The equation is given as:

$$NDVI = \frac{NIR-RED}{NIR+RED} \qquad \textbf{(Eq. 5)}$$

The required LST is then extracted by using emissivity and brightness temperature values as:

$$LST = \frac{BT}{1+\frac{L\lambda\,(BT)}{\rho}\ln(\varepsilon)} \qquad \textbf{(Eq. 6)}$$

In this way, the LST values for each pixel of our image are obtained in degrees Celsius.

2.4 Park Cool Island (PCI) Intensity

The intensity of park cooling is measured by the difference in surface temperature inside and outside of the park (Cao et al., 2010). The formula is given as

$$PCI = \Delta\mathrm{T} = T_u - T_p \qquad \textbf{(Eq. 7)}$$

where T_p is the average LST inside the park under study and T_u is the average LST of an urban area outside the park boundary. To examine the extent of cooling average temperatures were obtained from every 30-m buffer distance of each park up to a distance of around 510-m. The choice of a 30-meter buffer interval aligns with the resolution of the temperature map. Following the computation of Park Cool Island (PCI) values for each buffer interval, correlations are examined to assess the degree of relationship between these two parameters.

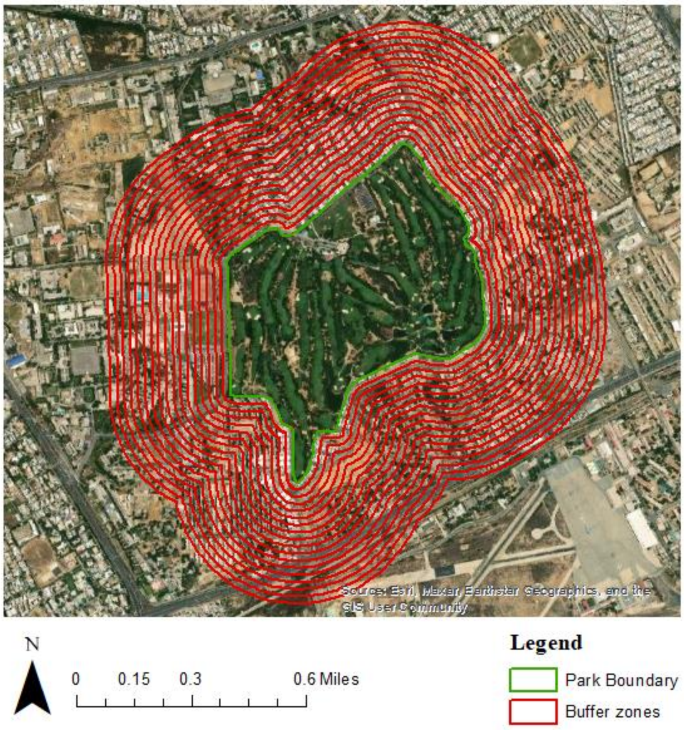

Fig. 2 Multiple ring buffers generated from Karachi Golf Club. ***Source:*** *World Imagery - Esri, Maxar, Earthstar Geographics, and the GIS User Community*

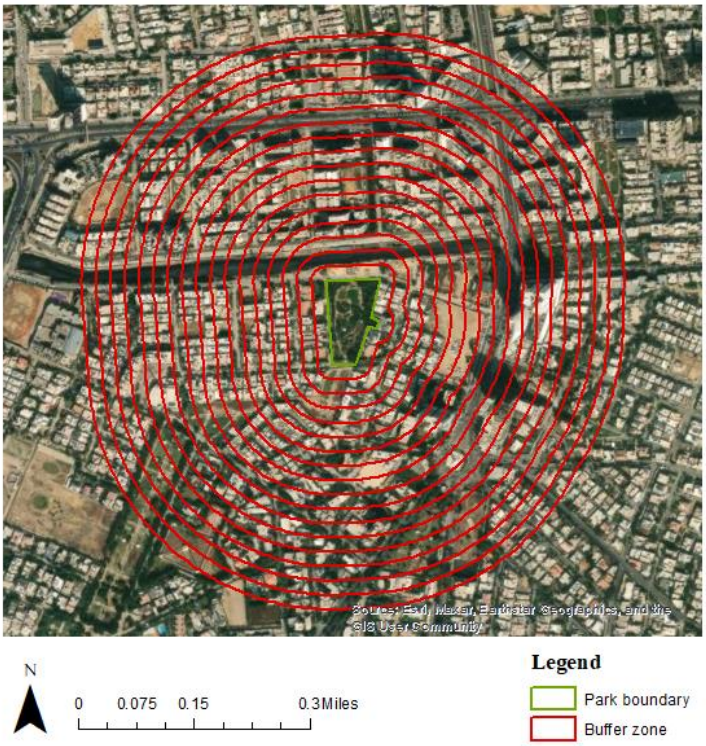

Fig. 3 Multiple ring buffers generated from Clifton Urban Forest. Source: World Imagery - Esri, Maxar, Earthstar Geographics, and the GIS User Community

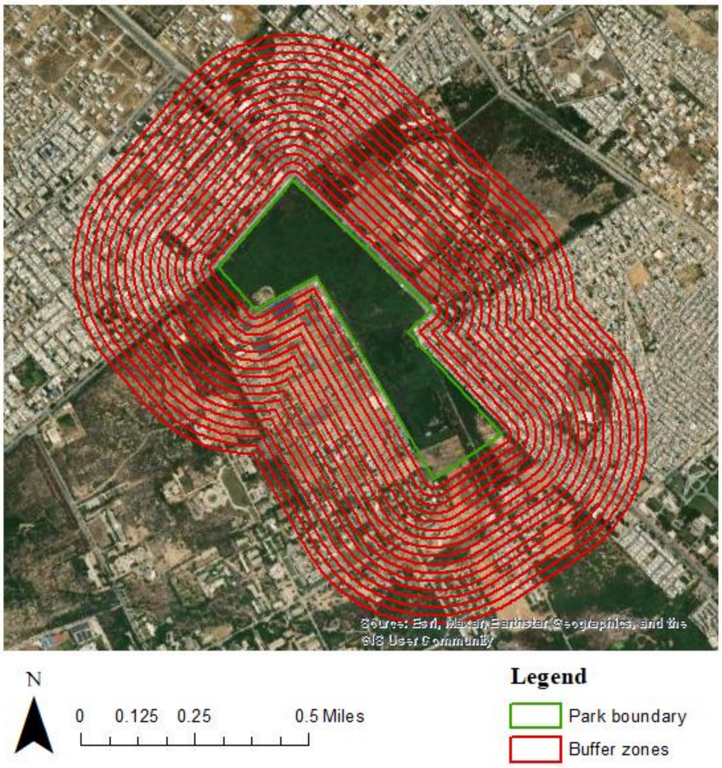

Fig. 4 Multiple ring buffers generated from UoK green space. Source: World Imagery - Esri, Maxar, Earthstar Geographics, and the GIS User Community

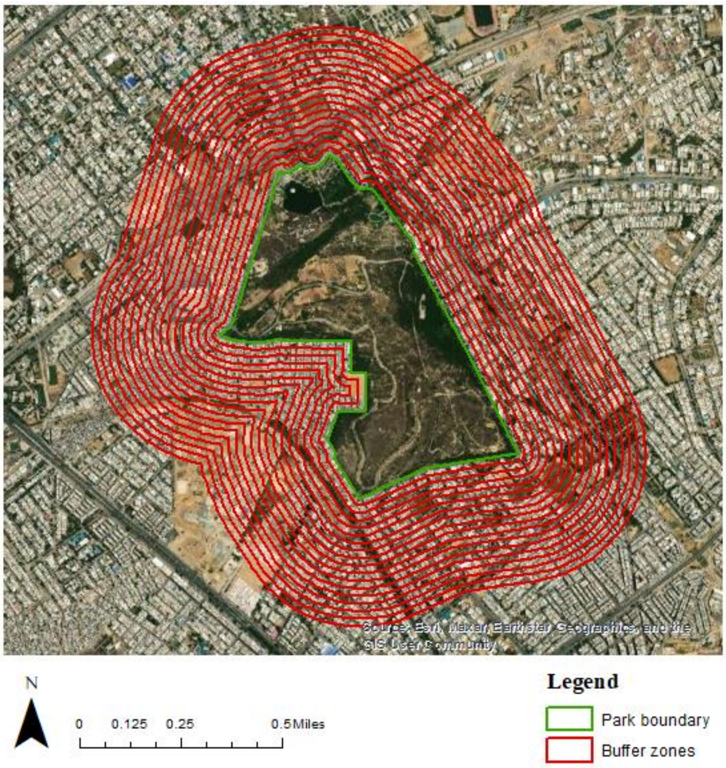

Fig. 5 Multiple ring buffers generated from Safari park. Source: World Imagery - Esri, Maxar, Earthstar Geographics, and the GIS User Community

2.5 Urban Thermal Field Variance Index (UTFVI)

The Urban Thermal Field Variance Index is a quantitative measure that expands on the idea of Urban Heat Island intensity. It examines the differences in LST throughout an urban area. A higher UTFVI score indicates a greater disparity in temperature, with certain areas of the city experiencing significantly higher temperatures compared to others. This discrepancy in temperature distribution is a defining feature of a pronounced Surface Urban Heat Island effect (SUHI). Various studies have employed the equation given by (Yong et al., 2006) to extract UTFVI from LST data.

$$\text{UTFVI} = \frac{\text{Ts}-\text{Tmean}}{\text{Tmean}} \qquad \textbf{(Eq. 8)}$$

Where T_s is the LST of the pixel and T_{mean} is the mean LST of the study area. UTFVI values are further categorized into six categories (None, weak, medium, strong, stronger, and strongest) based on (Liu and Zhang, 2011) to extract the areas having a high SUHI effect.

Table 1Threshold values of UTFVI and comfort level.

Urban Thermal Field Variation Index	**Urban Heat Island Phenomenon**	**Comfort Level**
<0	None	Excellent
0-0.005	Weak	Good
0.005-0.010	Middle	Normal
0.010-0.015	Strong	Bad
0.015-0.020	Stronger	Worse
>0.020	Strongest	Worst

2.6 Thermal Hotspots and Coldspots Analysis

To further analyze and identify specific locations having abnormally high land surface temperature values, the hotspot spatial clustering algorithm is used. The Getis Ord (Gi*) statistical method groups pixels of high positive z-score into hotspots (areas with high LST values surrounded by other high LST values), and high negative z-score into cold spots (areas with low LST values surrounded by other low LST values) (Ord and Getis, 1995).

The output of the Getis-Ord statistics method includes a z-score and a p-value for each feature, which can help in determining the statistical significance of the clusters. The z-score indicates the level of clustering of high or low values, while the p-value helps in determining if the clustering is significant or occurred by random chance. A cluster is deemed statistically significant if it consists of high values surrounded by other high-value features. Higher values of positive z-scores indicate a stronger clustering of high values, often referred to as a "hot spot." Conversely, when examining statistically significant negative z-scores, lower values signify a more intense clustering of low values, commonly known as a "cold spot."

$$G_i^* = \frac{\sum_j^n =1\, \omega_{i,j}\, x_j - \bar{X} \sum_j^n =1\, \omega_{i,j}}{S\sqrt{\frac{\left[n \sum_j^n =1\, \omega^2{}_{i,j} - \left(\sum_j^n =1\, \omega_{i,j}\right)^2\right]}{n-1}}} \qquad \textbf{(Eq. 9)}$$

$$\overline{X} = \frac{\sum_j^n=1\, x_j}{n} \qquad \textbf{(Eq. 10)}$$

$$\mathrm{S} = \sqrt{\frac{\sum_{\mathrm{j}}^{\mathrm{n}}=1\, \mathrm{x}^2{}_{\mathrm{j}}}{\mathrm{n}} - (\bar{X})^2} \qquad \textbf{(Eq. 11)}$$

Using the Getis-Ord Gi* statistic in ArcGIS, we examined data on LST to identify clusters of high and low temperatures, which allowed us to identify hotspots and coldspots throughout the study area. The output was generated in seven classes with varying confidence levels, 90%, 95%, and 99%.

By employing this approach, we gained insights into the spatial distribution of temperature anomalies, aiding in the identification of areas prone to extreme heat and cold events. Thereby enabling city officials to devise strategies for mitigating the UHI effect and fostering a sustainable environment.

Table 2 Hotspot classification through Gi approach.*

Gi* Hot-Spot Classes	**Confidence Levels**	**Gi* z-Score**
Coldspot 99	99%	< -2.58
Coldspot 95	95%	< -1.96
Coldspot 90	90%	< -1.65
Not significant	Not significant	-1.65 < z-score < 1.65
Hotspot 90	90%	> 1.65
Hotspot 95	95%	>1.96
Hotspot 99	99%	>2.58

3 Results

3.1 *Spatial Distribution of LST*

The analysis of Land Surface Temperature (LST) across Karachi revealed a clear spatial distribution pattern. As expected, densely built-up central areas, particularly Karachi Central and Malir district, exhibited significantly higher LST values within the urban boundary. This observation is particularly evident when examining the contrast between the cooler zones within the four selected urban parks and the surrounding built-up areas. These parks, including Karachi Golf Club, Clifton Urban Park, the green space within the University of Karachi, and Safari Park, all displayed lower LST values.

It's important to note that Karachi Central district, despite its overall higher LST, also showed some internal variations. The map suggests varying pockets of high and low LST within this district, possibly due to a mix of land cover types, including densely built areas alongside less developed zones with scattered vegetation. Whereas, Karachi South district, bordering the sea, benefits from the moderating effect of the Arabian Sea, resulting in lower LSTs compared to most inland districts.

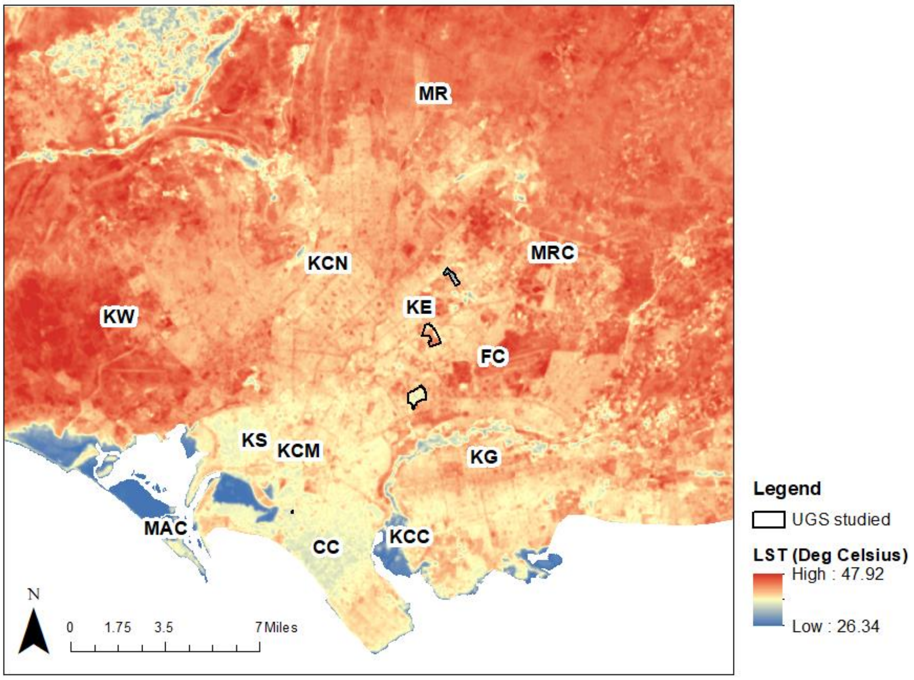

Fig 6 *Land Surface Temperature variation in the study area.*

Interestingly, when we look at the distribution of LST across the wider Karachi area, we find that the outskirts experience higher temperatures than the central districts. This may seem counterintuitive at first, but it can be explained by examining the land cover in these outlying areas. The image clearly shows that these outskirts are predominantly barren land, which tends to absorb more heat compared to the built-up areas that consist of a mix of surfaces such as roads, buildings, and vegetation.

Fig 3. shows the variation of LST at different distances from the boundaries of the selected parks. As the distance from the park decreases, indicating closer proximity to the park, the LST values generally decrease as well. This trend suggests that parks and other green spaces act as cooling zones, with temperatures significantly lower in the immediate vicinity compared to areas further away. Among the chosen parks, the University green space consistently displayed the lowest LST values. When measured at a 30-meter buffer distance, the minimum LST value was recorded at 37.21°C, and the average value across all distances was approximately 37.85°C. In contrast, the Karachi Golf Club showcased the highest LST values, with the highest LST reaching 39.81°C and an average LST of around 39.25°C.

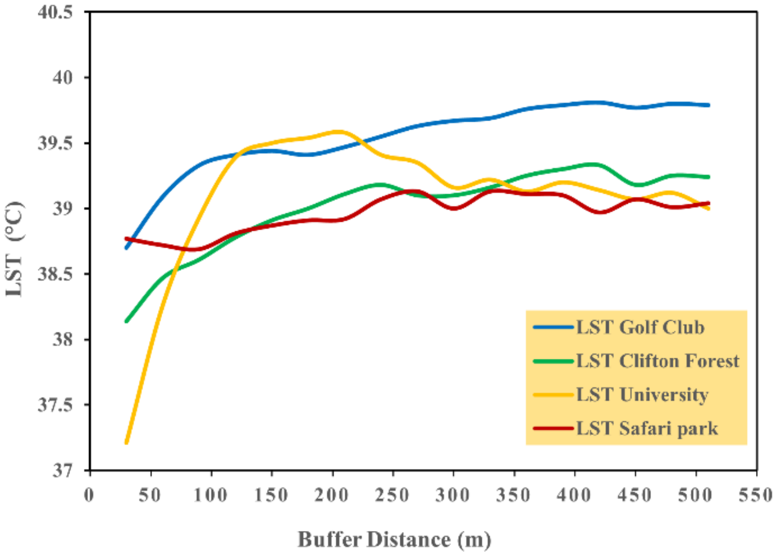

Fig 7 *Land Surface Temperature distribution of all selected parks across the buffer distance.*

3.2 *Green Space cooling effect*

The intensity values of urban green spaces in the study areas have varied across different buffer ranges. Although there are noticeable fluctuations in the temperature profiles, a general increasing pattern of strong positive correlation can be seen in all of the UGS. The temperature outside ‘Karachi Golf Club’ dropped slightly after 150m but then it gradually increased to 420m after which it became steadily constant.

A similar trend can be seen around ‘Clifton Urban Forest’ where the first turning point occurs at 240m, showing that the effective cooling distance for this park is around that distance. The correlation curve becomes constant after 420 meters. Such behaviour is most likely due to the small size of the park. Various studies have shown that the size and shape of the park are crucial factors in determining its cooling efficiency (Chang et al., 2007; Connors et al., 2013; Jaganmohan et al., 2016; Li et al., 2012; Shashua-Bar et al., 2009). A study conducted by Cheng et al., (2015) concluded that the park size accounts for approximately 73% and 80% of the variance observed in cooling distance and cooling area, respectively. Thus, when planning for an urban park according to its cooling potential, the size of the park becomes the primary factor to consider.

Table 3 Park Cooling Island Intensity for the selected UGS.

Park	**Buffer Range (m) / PCI intensity (ΔT)**																	
	T_p (C)	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510
Karachi Golf Club	37.14	1.56	1.95	2.19	2.27	2.3	2.27	2.33	2.41	2.49	2.53	2.55	2.62	2.65	2.67	2.63	2.66	2.65
Clifton Urban Forest	37.76	0.38	0.71	0.85	1.02	1.15	1.24	1.35	1.42	1.34	1.34	1.4	1.49	1.54	1.57	1.42	1.49	1.48
UoK Green Space	34.52	2.69	3.74	4.41	4.87	4.98	5.02	5.06	4.89	4.83	4.64	4.7	4.61	4.68	4.62	4.55	4.6	4.48
Safari Park	39.81	-1.04	-1.09	-1.12	-1	-0.94	-0.9	-0.89	-0.74	-0.68	-0.81	-0.68	-0.7	-0.71	-0.84	-0.74	-0.8	-0.77

Upon analysis of the University's green space, it became evident that beyond 240 meters from the park boundary, the cooling effect stabilized at approximately 4.8°C. This leveling off in cooling intensity can be attributed to patches of barren land and residential buildings surrounding the area suggesting that factors other than park characteristics may influence the cooling effect on surrounding areas. Furthermore, the neglect of maintenance for vacant land within the university exacerbates heat absorption and comfort levels.

The relation established in the 'Safari Park' exhibited an unusual trend, as the intensity values were recorded as negative. Upon closer examination of the park's topography, it becomes apparent that the trees are mostly concentrated along the edges, while the central areas have limited tree coverage. This sort of pattern leads to erratic fluctuations in the recorded Land Surface Temperature. Additionally, the presence of a natural lake further complicates the observed data trend. This underscores the importance of urban planners and administrators to prioritize the preservation and enhancement of Karachi's largest park for effective urban temperature mitigation.

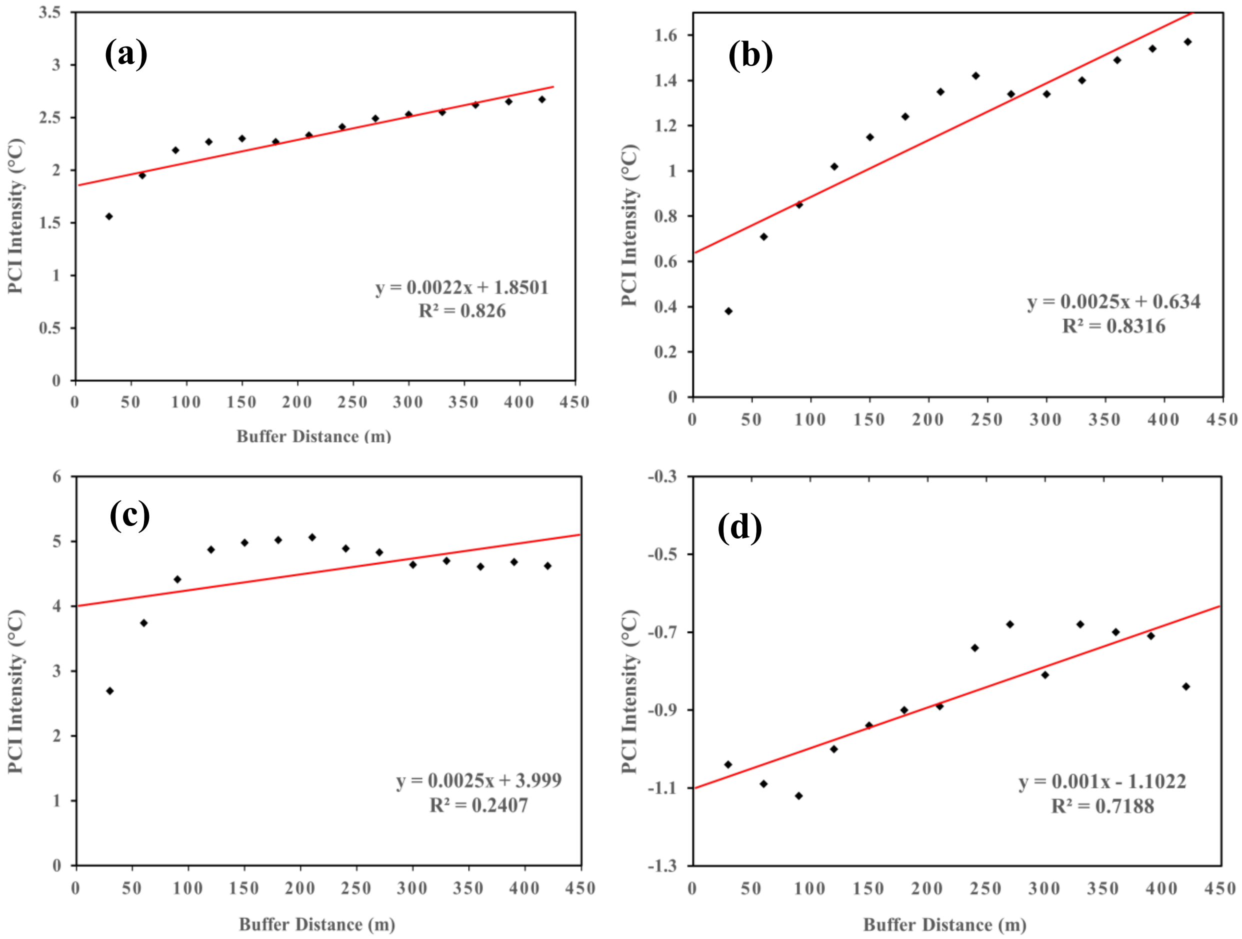

Fig 8 *Relationship between cooling effects intensity and buffer range at **(a)** Karachi golf club **(b)** Clifton Urban Forest **(c)** UoK green space **(d)** Safari Park.*

The R^2 coefficients for the ‘Karachi Golf Club’, ‘Clifton Urban Forest’, ‘University green space’, ‘Safari Park’ and are 0.826, 0.832, 0.241 and 0.718 respectively. These results strongly suggest that urban green spaces can significantly reduce the temperature of nearby built-up areas.

3.2 *Thermal Comfort Levels (UTFVI)*

The analysis conducted in May 2022 on the Urban Thermal Field Variance Index (UTFVI) for the urban area of Karachi revealed a clear spatial pattern in the fluctuations of land surface temperature. Districts bordering the Arabian Sea, such as Karachi South, Clifton, and Korangi, consistently showed lower UTFVI values, indicating cooler surface temperatures that are likely influenced by the sea breeze.

On the other hand, inland districts like West, Malir, and Malir Cantonment exhibited the strongest urban heat island phenomena, indicating the highest levels of ecological discomfort. These areas are characterized by poor urban planning, considerable amounts of barren land, and a lack of urban green spaces. This noticeable urban heat island effect observed significantly disrupted the overall UHI intensity across the city. A similar conclusion was drawn by Hassan et al., (2021) that Karachi ranks poorly in ecological evaluation compared to other South Asian cities studied.

Upon examining the Central, East, and Faisal Cantonment districts, we found that the thermal comfort levels were notably favourable. This can be credited to the presence of urban green spaces. This highlights the significant role that such spaces play in cooling the temperature in surrounding areas.

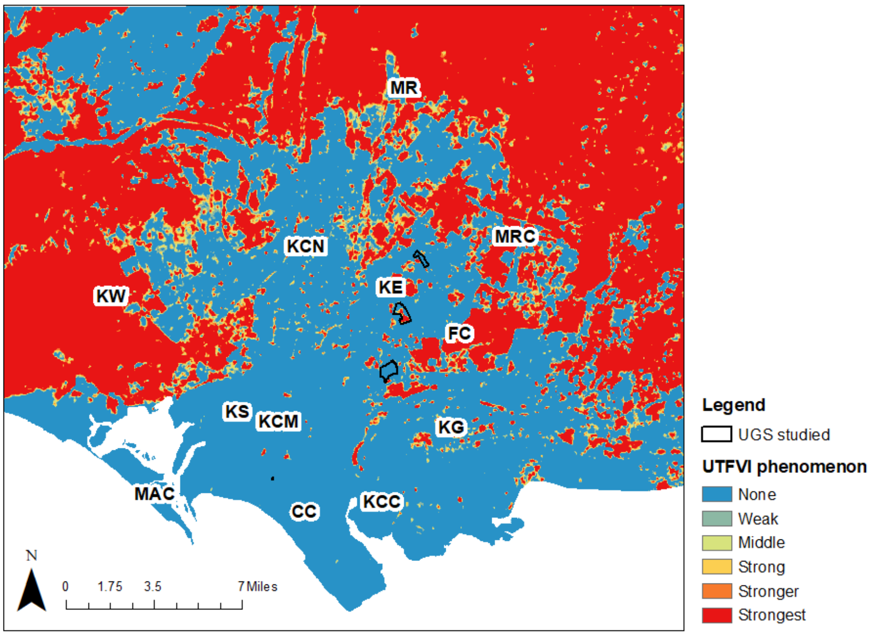

Fig 9 *Spatial trend of UTFVI in the study area.*

3.3 Spatial Hotspot Analysis

To conduct a thorough analysis of the thermal dynamics within the urban environment of Karachi, hotspot analysis was done to identify localized clustering of high and low surface temperatures in the study area. Fig 10 shows hotspot and coldspot areas.

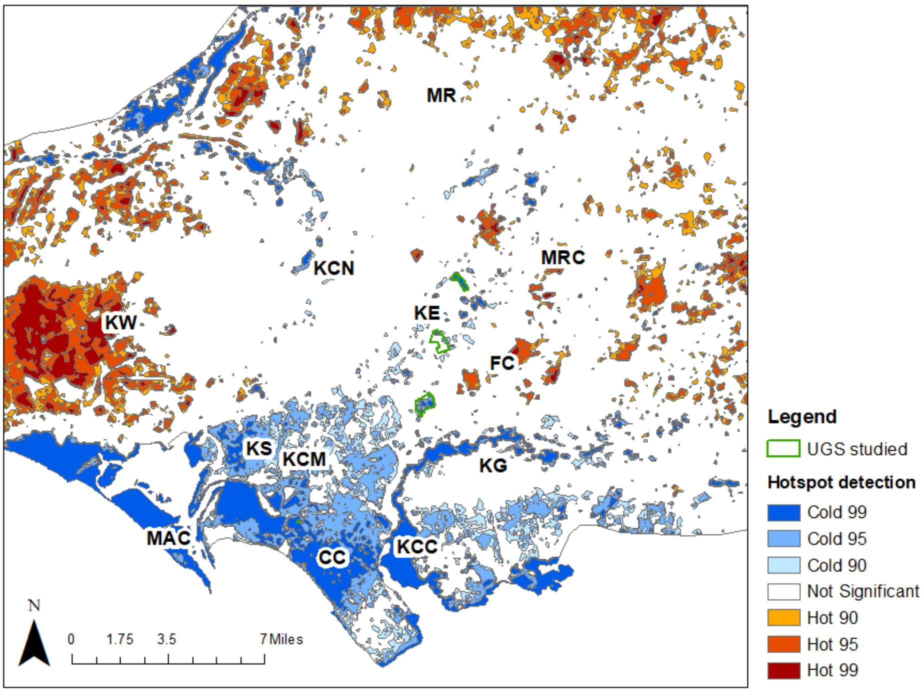

Fig 10 *Location of the hot/cold spots within Karachi municipality*

The results indicate that all of the districts in the South and Southeast of the city are dominated by coldspot regions. This shows that these areas are more resilient towards temperature variations due to their proximity to the Arabian Sea and access to cold breezes in the summer months. The mangrove belt stretching along the coastal line of Karachi is another reason that the surrounding areas including Clifton, Clifton cantonment, Korangi creek area, Kiamari town, P.E.C.H.S, etc. are relatively cool. Despite their coastal location, these areas can still be affected by heatwaves. Factors such as high humidity, urban compactness, poorly ventilated high-rise buildings, and low-quality construction materials contribute to increased urban heat island intensity in the South (Cheema, 2015).

Analysis of Karachi's ‘Central’ and ‘Eastern’ districts revealed a strong association between urban green spaces and reduced heat stress. These areas displayed fewer hotspots and more coldspots compared to adjacent areas with limited green cover, like ‘Faisal Cantonment’. We concluded that Faisal Cantonment contributes to a higher prevalence of hotspots because of the lack of urban green spaces (UGS) resulting in increased LST.

A starkly different scenario emerges as one moves away from the coastal regions. Karachi West is predominantly engulfed in hotspot areas, with 76% of total hotspots concentrated in this district. Analysis of the land cover in Mauripur Union Council within Karachi West district reveals a predominance of vacant land, a characteristic shared by other areas such as Mangopir and Gaho Pat, excluding the mangrove-protected region. Additionally, the presence of PAF Base Masroor, Karachi's largest air force base, contributes to a significant lack of vegetation in the area. This extensive vacant land, devoid of trees and other green cover, exacerbates heat stress. As a result, unusually high surface temperatures are prevalent, with the district recording an average Land Surface Temperature (LST) of 42.13 °C.

Malir District, encompassing a vast 71% of Karachi's total area, presents a concerning pattern as well. Despite its vast size, the district is dominated by vacant barren land. This lack of vegetation coincides with the presence of numerous scattered hotspots, highlighting the link between limited greenery and elevated surface temperatures. To address this issue and improve Karachi's overall thermal comfort, developing these vacant areas into strategically planned urban green spaces is highly recommended. Such an initiative could significantly reduce the hotspots during scorching summers and cool down the surrounding environment, benefiting not only Malir but also the whole of Karachi.

4 Discussion

This study investigated the potential of Urban Green spaces to mitigate Karachi's Urban Heat Island (UHI) effect. Our analysis revealed a clear benefit – the presence of UGS significantly reduces Land Surface Temperature (LST) within parks compared to their surroundings. All four green spaces studied exhibited a positive correlation between cooling intensity and distance from the park boundary, with a mean cooling distance of 250 meters, highlighting their cooling efficacy. The cooling distance can be significantly increased by expanding these parks to a much larger area. Numerous studies have consistently demonstrated that the size and area of a park play a crucial role in determining its cooling efficiency (Bowler et al., 2010; Chen et al., 2022; Lin et al., 2015b). A larger green park area leads to a greater cooling effect, resulting in more extensive cooling under similar surrounding conditions. Additionally, the findings revealed that all four urban green spaces analyzed in this study corresponded to cold spots with a 99% level of confidence.

The research also highlights the detrimental impact of lacking UGS. Areas with limited green cover displayed the worst ecological comfort levels, as depicted by high UTFVI values and numerous hotspots. These findings paint a concerning picture of Karachi's future. The conversion of natural vegetation to built-up areas and the neglect of UGS development have significantly deteriorated Karachi's overall thermal comfort. Therefore, it is imperative to promptly acknowledge and take action to address these issues.

Prioritizing the construction of green spaces, particularly in identified hotspot areas, offers a clear path towards a cooler and more livable Karachi. Existing parks also need attention in a way that increasing tree density and timely maintenance can greatly improve their cooling efficiency. In such an environment, the surrounding air does not flow out, creating high-pressure areas that help maintain the cooler microclimate (Arshad et al., 2020b).

It is crucial to evaluate ongoing land-use changes and conduct urban comfort analyses to inform better policymaking and decision-making regarding the preservation of green spaces in cities, ultimately enhancing city life. By pinpointing specific areas within urban centres exhibiting significant disparities in UHI-based UTFVI and conducting detailed thermal hotspot analysis, we can gain valuable insights into where green cover is most urgently needed. This enables the strategic allocation of resources to enhance urban resilience, improve the health conditions of its inhabitants, and promote a more sustainable and equitable urban environment. Embracing the power of trees and green spaces is essential for Karachi's climate adaptation. Educating the public and city government about the crucial role of Urban Green Spaces (UGS) and actively converting vacant land into urban forests can create a more sustainable and livable city for all.

5 Conclusion

This study investigated the critical role of urban green spaces (UGS) in mitigating the Urban Heat Island (UHI) effect in Karachi, a densely populated metropolis. Our analysis revealed a positive correlation between Park Cool Island Intensity (PCI) and buffer range, confirming that UGS significantly cools the surrounding microclimate. The Karachi Golf Club and Clifton Urban Forest emerged as the most efficient cooling spaces, with R^2 values exceeding 0.8. While the other two examined green spaces (Safari Park and Karachi University green space) also showed positive correlations, their cooling efficiency was very low likely due to a lack of maintenance and unoptimized layout.

Furthermore, examining the UTFVI and the thermal Hotspots provided valuable insights into Karachi's thermal patterns. The analysis identified a distinct spatial distribution of ecological discomfort, with the western district experiencing the most severe UHI impact due to a lack of UGS and extensive vacant land. Notably, the only inland regions experiencing comparatively lower heat stress were those equipped with urban parks. These findings demonstrate the crucial role of UGS as a lifeline against the intensifying UHI effect and the growing threat of climate change-driven heat waves. Future research could expand upon this work by incorporating land-use/land-cover classification of the study area, along with incorporating night-time LST datasets. This will enable a more comprehensive understanding of the city's microclimate dynamics.

Acknowledgement

The authors wish to acknowledge the United States Geological Survey (USGS) for the provision of data used for this study.

References

1. Ali, S.A., Parvin, F., Ahmad, A., 2023. Retrieval of Land Surface Temperature from Landsat 8 OLI and TIRS: A Comparative Analysis Between Radiative Transfer Equation-Based Method and Split-Window Algorithm. Remote Sens Earth Syst Sci 6, 1–21.
2. Aram, F., García, E.H., Solgi, E., Mansournia, S., 2019. Urban green space cooling effect in cities. Elsevier BV 5, e01339–e01339.
3. Arifeen, M., 2016. Karachi dominance: economic and financial hub of Pakistan. [WWW Document]. Pak Gulf Econ.
4. Arshad, A., Ashraf, M., Sundari, R.S., Qamar, H., Wajid, M., Hasan, M. ul, 2020a. Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi. International Journal of Disaster Risk Reduction 46, 101468.
5. Arshad, A., Ashraf, M., Sundari, R.S., Qamar, H., Wajid, M., Hasan, M. ul, 2020b. Vulnerability assessment of urban expansion and modelling green spaces to build heat waves risk resiliency in Karachi. International Journal of Disaster Risk Reduction 46, 101468.
6. Baqa, M.F., Lu, L., Chen, F., Nawaz-Ul-huda, S., Pan, L., Tariq, A., Qureshi, S., Li, B., Li, Q., 2022. Characterizing Spatiotemporal Variations in the Urban Thermal Environment Related to Land Cover Changes in Karachi, Pakistan, from 2000 to 2020. Remote Sens (Basel) 14.
7. Berk, A., Bernstein, L.S., Robertson, D.C., 1987. MODTRAN: A Moderate Resolution Model for LOWTRAN.
8. Bowler, D.E., Buyung-Ali, L., Knight, T.M., Pullin, A.S., 2010. Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landsc Urban Plan.
9. Cao, X., Onishi, A., Chen, J., Imura, H., 2010. Quantifying the cool island intensity of urban parks using ASTER and IKONOS data. Landsc Urban Plan 96, 224–231.
10. Chang, C.R., Li, M.H., Chang, S.D., 2007. A preliminary study on the local cool-island intensity of Taipei city parks. Landsc Urban Plan 80.
11. Cheema, A.R., 2015. High-rise buildings worsened heatwave. Nature 2015 524:7563 524, 35–35.
12. Chen, A., Yao, X., Sun, R., Chen, L., 2014. Effect of urban green patterns on surface urban cool islands and its seasonal variations. Elsevier BV 13, 646–654.
13. Chen, M., Jia, W., Yan, L., Du, C., Wang, K., 2022. Quantification and mapping cooling effect and its accessibility of urban parks in an extreme heat event in a megacity. J Clean Prod 334.
14. Cheng, X., Wei, B., Chen, G., Li, J., Song, C., 2015. Influence of Park Size and Its Surrounding Urban Landscape Patterns on the Park Cooling Effect. J Urban Plan Dev 141.
15. Connors, J.P., Galletti, C.S., Chow, W.T.L., 2013. Landscape configuration and urban heat island effects: Assessing the relationship between landscape characteristics and land surface temperature in Phoenix, Arizona. Landsc Ecol 28.
16. Georgiana, G., Urițescu, B., Grigoraș, G., 2018. SPATIAL HOTSPOT ANALYSIS OF BUCHAREST'S URBAN HEAT ISLAND (UHI) USING MODIS DATA. Geographical Series 18, 14–22.
17. Goswami, J., Roy, S., Sudhakar, S., 2013. A Novel Approach in Identification of Urban Hot Spot Using Geospatial Technology: A Case Study in Kamrup Metro District of Assam. International Journal of Geosciences 04.

18. Hassan, T., Zhang, J., Prodhan, F.A., Pangali Sharma, T.P., Bashir, B., 2021. Surface urban heat islands dynamics in response to lulc and vegetation across south asia (2000–2019). Remote Sens (Basel) 13.
19. Jaganmohan, M., Knapp, S., Buchmann, C.M., Schwarz, N., 2016. The Bigger, the Better? The Influence of Urban Green Space Design on Cooling Effects for Residential Areas. J Environ Qual 45.
20. Jauregui, E., 1990. Influence of a large urban park on temperature and convective precipitation in a tropical city. Energy Build 15.
21. Ko, Y.-J., Cho, K.-H., 2020. Analysis of Areas Vulnerable to Urban Heat Island Using Hotspot Analysis - A Case Study in Jeonju City, Jeollabuk-do -. Journal of the Korean Institute of Landscape Architecture 48, 67–79.
22. Li, X., Zhou, W., Ouyang, Z., Xu, W., Zheng, H., 2012. Spatial pattern of greenspace affects land surface temperature: Evidence from the heavily urbanized Beijing metropolitan area, China. Landsc Ecol 27.
23. Lillesand, T.M., Kiefer, R.W., 1979. Remote sensing and image interpretation. Remote sensing and image interpretation.
24. Lin, W., Yu, T., Chang, X., Wu, W., Zhang, Y., 2015a. Calculating cooling extents of green parks using remote sensing: Method and test. Landsc Urban Plan 134.
25. Lin, W., Yu, T., Chang, X., Wu, W., Zhang, Y., 2015b. Calculating cooling extents of green parks using remote sensing: Method and test. Landsc Urban Plan 134.
26. Liu, L., Zhang, Y., 2011. Urban heat island analysis using the landsat TM data and ASTER Data: A case study in Hong Kong. Remote Sens (Basel) 3.
27. Mackey, C.W., Lee, X., Smith, R.B., 2012. Remotely sensing the cooling effects of city scale efforts to reduce urban heat island. Build Environ 49, 348–358.
28. Mavrakou, T., Polydoros, A., Cartalis, C., Santamouris, M., 2018. Recognition of thermal hot and cold spots in Urban areas in support of mitigation plans to counteract overheating: Application for Athens. Climate 6.
29. Mentaschi, L., Duveiller, G., Zulian, G., Corbane, C., Pesaresi, M., Maes, J., Stocchino, A., Feyen, L., 2022. Global long-term mapping of surface temperature shows intensified intra-city urban heat island extremes. Global Environmental Change 72.
30. Nor, S., Buyadi, A., Naim, W.M., Mohd, W., Misni, A., 2015. Methodology Used in Quantifying Green Space Cooling Effect on the Surrounding Urban Areas: A Case Study of Petaling District, Selangor. Research Methodology for Built Environment and Engineering Shah Alam.
31. Oke, T.R., 1982. The energetic basis of the urban heat island. Quarterly Journal of the Royal Meteorological Society 108, 1–24.
32. O'Malley, C., Piroozfarb, P.A.E., Farr, E.R.P., Gates, J., 2014. An Investigation into Minimizing Urban Heat Island (UHI) Effects: A UK Perspective. Energy Procedia 62, 72–80.
33. Ord, J.K., Getis, A., 1995. Local Spatial Autocorrelation Statistics: Distributional Issues and an Application. Geogr Anal 27, 286–306.
34. Rizvi, S.H., Fatima, H., Iqbal, M.J., Alam, K., 2020. The effect of urbanization on the intensification of SUHIs: Analysis by LULC on Karachi. J Atmos Sol Terr Phys 207, 105374.
35. Sajjad Hussain Sajjad, Nadège Blond, Rabia Batool, Safdar Ali Shirazi, Khadija Shakrullah, M. Nasar Bhalli, 2015. Study of Urban Heat Island of Karachi by Using Finite Volume Mesoscale Model. Journal of Basic & Applied Sciences 11.
36. Shashua-Bar, L., Pearlmutter, D., Erell, E., 2009. The cooling efficiency of urban landscape strategies in a hot dry climate. Landsc Urban Plan 92, 179–186.

37. Statistics, P.B. of, 2017. PROVISIONAL SUMMARY RESULTS OF 6TH POPULATION AND HOUSING CENSUS-2017 | Pakistan Bureau of Statistics. Provisional summary result 2017.
38. UN DESA, 2018. 2018 Revision of World Urbanization Prospects. United Nations News.
39. Wang, C., Chang, H.-T., 2020. Hotspots, Heat Vulnerability and Urban Heat Islands: An Interdisciplinary Review of Research Methodologies. Canadian Journal of Remote Sensing 46, 532–551.
40. Weng, Q., 2009. Thermal infrared remote sensing for urban climate and environmental studies: Methods, applications, and trends. ISPRS Journal of Photogrammetry and Remote Sensing 64, 335–344.
41. Weng, Q., Quattrochi, D.A., 2006. Thermal remote sensing of urban areas: An introduction to the special issue. Remote Sens Environ 104, 119–122.
42. Wu, X., Liu, Q., Huang, C., Li, H., 2022. Mapping Heat-Health Vulnerability Based on Remote Sensing: A Case Study in Karachi. Remote Sens (Basel) 14, 1590.
43. Xu, X., Sun, S., Liu, W., García, E.H., He, L., Cai, Q., Xu, S., Wang, J., Zhu, J., 2017. The cooling and energy saving effect of landscape design parameters of urban park in summer: A case of Beijing, China. Energy Build 149, 91–100.
44. Yang, L., Qian, F., Song, D.X., Zheng, K.J., 2016. Research on Urban Heat-Island Effect. Procedia Eng 169, 11–18.
45. Yang, P., Xiao, Z., Ye, M.-S., 2016. Cooling effect of urban parks and their relationship with urban heat islands. Atmospheric and Oceanic Science Letters.
46. Yao, X., Yu, K., Zeng, X., Lin, Y., Ye, B.-J., Shen, X., Liu, J., 2022. How can urban parks be planned to mitigate urban heat island effect in “Furnace cities” ? An accumulation perspective. J Clean Prod 330, 129852.
47. Yong, Z., Tao, Y., fa Gu, X., Zhang, Y., Yu, S., Zhang, W., Li, X., 2006. Land Surface Temperature Retrieval from CBERS-02 IRMSS Thermal Infrared Data and Its Applications in Quantitative Analysis of Urban Heat Island Effect. National Remote Sensing Bulletin.
48. Zargari, M., Mofidi, A., Entezari, A., Baaghideh, M., 2024. Climatic comparison of surface urban heat island using satellite remote sensing in Tehran and suburbs. Scientific Reports 2024 14:1 14, 1–23.