



URBAN HEAT ISLAND INTENSIFICATION IN COACHING INDUSTRY CLUSTERS: SPATIO-TEMPORAL ANALYSIS OF SURFACE TEMPERATURE, BUILT-UP EXPANSION, AND MOISTURE DYNAMICS IN KOTA, INDIA (2000–2020)

¹ARISHA HUSSAIN, ²Dr. AJAY VIKRAM SINGH CHANDEL

¹PhD Research Scholar, ²Professor

¹Department of Geography,

¹Kota University, Kota, India

Abstract: Rapid urbanisation driven by sector-specific economic activities presents distinct and underexplored patterns of thermal environment modification. This study investigates the Urban Heat Island (UHI) effect in Kota, Rajasthan — India's largest coaching industry hub accommodating over 250,000 competitive examination students annually — through integrated multi-temporal remote sensing analysis. Landsat Collection 2, Level-2 satellite imagery from 2000 and 2020 was utilised to compute and map three complementary spectral indices: Land Surface Temperature (LST), Modified Normalised Difference Water Index (MNDWI), and Normalised Difference Built-up Index (NDBI). Zonal statistics were extracted within 500 m, 1 km, and 2 km buffer zones centered on twelve major coaching institute clusters, providing spatially explicit UHI intensity measurements at progressively greater distances from the coaching epicentre. City-wide mean LST increased by +2.67°C between 2000 and 2020 (27.04°C to 29.71°C), with minimum temperatures rising by +3.92°C, reflecting progressive destruction of natural cooling surfaces. Coaching institute buffer zones exhibited surface temperatures consistently 2.76°C to 3.35°C above the city mean in 2020, with the 500 m zone recording a mean LST of 33.06°C. NDBI maximum values increased from +0.148 to +0.216, confirming extensive built-up densification commensurate with 44.2% growth in urban impervious cover. MNDWI analysis reveals spatial polarisation between an increasingly moisture-deficient urban core and an expanding irrigated agricultural periphery. The convergence of high NDBI, low MNDWI, and elevated LST values within coaching clusters constitutes a thermodynamically coherent UHI system driven by impervious surface expansion, elimination of evapotranspirative cooling, and high anthropogenic heat flux. These findings establish coaching-industry-driven urbanisation as a distinct and significant driver of surface UHI intensification, with direct implications for student welfare, public health policy, and thermally responsive urban planning in India's rapidly growing educational cities.

Index Terms – Urban Heat Island; Land Surface Temperature; MNDWI; NDBI; Kota; Coaching Institute; Landsat; Spatio-Temporal Analysis; Rajasthan; Educational Urbanisation

I. Introduction

One of the most widely documented effects of the landscape surface alteration brought about by human activity is the Urban Heat Island (UHI) phenomenon, where urban environments experience an objectively higher level of surface and near-surface air temperatures as compared to their rural environment (Oke, 1982; Arnfield, 2003). With the growing and intensifying cities around the world, UHI impacts increase thermal discomfort, raise cooling energy use, harm air quality, and overburden urban populations with disproportionate health impacts (Peng et al., 2012; Heaviside et al., 2017). Given the rapid urbanisation of economies like India, where urban populations are set to exceed 600 million by 2031 (UN-Habitat, 2022), the processes and local geometries of UHI formation are an acute scientific and policy concern.

Although the UHI literature has thoroughly covered industrial, commercial and residential urbanisation, the thermal consequences of urban growth driven by specific sector needs and demand are relatively unexplored. Urbanisation through education, that is, cities develop at a high rate in particular due to the agglomeration of educational establishments, students, and the surrounding services, creates characteristic urban forms and land-use densities that can create unique UHI patterns. Kota, a city in the Hadoti plateau of southern Rajasthan, India (25°11'N, 75°51'E; elevation 274 m a.s.l.), is an archetypal and unique example of urbanisation on a large scale in education.

Over the last 30 years, Kota has become the most important coaching capital in India: an urban area, the economy of which, spatial organization, and demographic structure are structurally oriented to the preparation of students to take competitive entrance exams, mainly the Joint Entrance Examination (JEE) to engineering and the National Eligibility cum Entrance Test (NEET) to medicine. Student populations of more than 250,000 annually (Kota District Administration, 2023) have created the need to house large numbers of students in high-density residential facilities, commercial intensive development, and growth of transport infrastructure, and spreading campuses of coaching institutes. The urban economic landscape is dominated by twelve large coaching institutes such as Allen Career Institute, Resonance Eduventures, Bansal Classes, Career Point, Vibrant Academy, Motion Education, Aakash Institute, FIITJEE, Narayana Group, RAO IIT Academy, Brilliant Tutorials, and Etoos Education, which are concentrated nodes of built-up intensification.

Although the literature on the Indian urban thermal environment can be characterized by the outstanding urban development history of Kota, regardless of its enormous size (Mohan et al., 2012; Ramachandra et al., 2015; Ranagalage et al., 2018), none of the studies has studied the UHI processes in this city and explored whether the urbanisation of the coaching industry can generate a spatially coherent This forms a huge gap in applied urban climatology as well as the new literature on the environmental impact of the competitive examination system in India.

The most suitable and methodologically consistent method to measure Surface Urban Heat Island (SUHI) over the multi-decadal time scales is remote sensing. The Landsat archive - more than five decades of continuous global coverage - can be used to perform strong temporal comparisons of the Land Surface Temperature (LST) and related land surface indices with a consistent spatial resolution (30 m). LST, which is a derivative of thermal infrared satellite observations, is the standard proxy variable of the intensity of SUHI (Voogt and Oke, 2003; Weng, 2009). Complementary spectral indices — the Modified Normalised Difference Water Index (MNDWI; Xu, 2006) and the Normalised Difference Built-up Index (NDBI; Zha et al., 2003) measure the availability of surface moisture and built-up density which are the most significant environmental controls of surface thermal behaviour.

The paper aims to achieve four interconnected goals, which include: (i) calculating and mapping LST, MNDWI and NDBI of Kota Municipal Area in 2000 and 2020 based on the USGS Landsat Collection 2, Level-2 products; (ii) quantifying and characterizing the spatio-temporal changes in surface thermal conditions and environmental drivers.

1. Theoretical Framework and Literature Review

1.1 Surface Urban Heat Island: Mechanisms and Measurement

Howard (1818) in London was the first to describe the UHI effect systematically and Oke (1973, 1982) was the first to put forward a consistent energetic explanation of urban-rural temperature differentials. UHI formation is driven by four major thermodynamic processes: (i) the substitution of vegetated and wet surfaces by thermally massive and low-albedo non-porous surfaces that enhance the amount of absorbed solar radiation and sensible heat flux; (ii) the decrease or removal of evapotranspiration that transfers latent heat flux into sensible heat, (iii) the geometry of urban canyons, which increases the trapping of longwave radiation; and (iv) anthropogenic heat generation from vehicles, industry, and building systems.

Voogt and Oke (2003) separated the surface UHI (SUHI) which is measurable as land surface temperature differences, using thermal remote sensing, and the canopy-layer UHI which is measured as air temperature at the network. Although these are associated yet separate phenomena, SUHI intensity is the most operational useful measure of city-wide spatio-temporal analysis due to the presence of regular satellite thermal archives. World syntheses have recorded median daytime SUHI of 1.50°C to 4.0°C in various climatic regions with extreme values of more than 10°C in arid and semi-arid urban environments (Zhao et al., 2014; Peng et al., 2012).

In urban areas, SUHI intensities of 3°C have been measured in Delhi (Mohan et al., 2012) and Ramachandra et al. (2015) in Bengaluru of +2.5°C over a thirty-year period, in line with urban built-up growth of 8–45 percent of total land area. Similar patterns of warming were found in Dhaka and Kolkata by Halder et al. (2021). The UHI in semi-arid cities is aggravated: the interplay of high background temperatures, low background humidity, and rapid urbanisation based on moisture exhaustion leads to especially unfavourable thermal conditions (Morakinyo et al., 2017).

1.2 Spectral Indices for SUHI Analysis

The Modified Normalised Difference Water Index (MNDWI) introduced by Xu (2006) as an extension of McFeeters (1996) NDWI, takes advantage of the fact that difference in reflectance of water surfaces and built-up areas in the green (0.52–0.60 μm) and SWIR1 (1.55–1.75 μm) bands: $MNDWI = (\rho_{Green} - \rho_{SWIR}) / (\rho_{Green} + \rho_{SWIR})$

SWIR radiation is highly absorbed by water but reflected by green wavelengths, and this results in positive values of MNDWI; the spectral behaviour is just the opposite in impervious surfaces, resulting in negative values. MNDWI is negatively related to LST (Guha et al., 2018): the availability of surface moisture (in the water bodies, moist soils, or vegetated surfaces) supports latent heat flux via evapotranspiration, decreasing sensible heat flux and surface temperatures. It is therefore a proximate thermal driver by its removal (by replacing with impervious cover).

The Normalised Difference Built-up Index (NDBI) is a built-up index developed by Zha et al. (2003) which takes advantage of the greater SWIR relative to NIR reflectance of built-up surfaces over vegetation: $NDBI = (\rho_{SWIR} - \rho_{NIR}) / (\rho_{SWIR} + \rho_{NIR})$

Surfaces with buildings have positive values of NDBI; water and vegetation are negative. NDBI has a positive relationship with LST (He et al., 2011; Chen et al., 2006): impervious surfaces generally have lower albedo, larger thermal admittance, and insignificant evapotranspiration as compared to vegetated surfaces, resulting in high sensible heat flux and surface temperatures. Guha et al. (2018) reported significant positive NDBI-LST and negative MNDWI-LST relationships in urban settings of Mediterranean and South Asia.

1.3 Urbanisation and Thermal Environment of Education

Institutional land use — universities, hospitals, and industrial estates — and local UHI formation have not been systematically studied despite the large footprints of these developments. Indian city coaching institutes are linked to unique urban morphologies: high-density paying guest hotels (locally known as 'PG hostels'), intensive retail and food service nodes, high pedestrian and vehicular density, long working hours leading to continuous anthropogenic heating, and high-speed informal construction, focusing on the floor area and neglecting thermal performance (Kumar and Singh, 2019). These morphological features interact to produce locally strong anthropogenic heat fluxes overlaid on radiative heating on impervious surfaces, which may enhance the formation of UHIs beyond that which would be anticipated by generalised indices of urbanisation.

The stress due to temperature has reported effects on the mental ability, study output, and health of the student groups. Seppanen et al. (2006) determined that indoor temperatures exceeding 25°C are linked to quantifiable performance damages in cognitive tasks, whereas Sheffield et al. (2013) reported that youths in urban regions with high temperatures experienced morbidity due to heat. As students in the coaching hub of Kota spend long hours in crowded and poorly-ventilated housing and walk or cycle through thermally-stressful outdoor areas to access coaching facilities, surface UHI increases have direct implications on the wellbeing and performance of the 250,000+ students who form the bulk of the student population.

2. Study Area

The administrative boundary within the study area (the Kota Municipal Corporation Area, approximately 320 km²) lies within the Hadoti plateau area of southeastern Rajasthan, India. The Chambal River — a perennial river and the main hydrological element of the area — cuts the city in a large north-south direction, creating important landscape feature and thermal regulating zone. The Köppen climate system of Kota is BSh (hot semi-arid), with average yearly temperatures above 25°C, wet monsoon rainfall (July–September; about 700 mm/per annum) and dry seasons when water resources are scarce and the sun is placed above the surface.

City morphology is indicative of its two economic identities. In the north and West, there are already developed industrial zones, such as Chambal Fertilisers complex and chemical manufacturing plants. The focus of this new urban development has been the southern and south-central areas, which form the coaching center, with the largest density of major coaching centers, student housing, and related commercial businesses. The northeast edge is typified by agricultural land which enjoys the irrigation of the Chambal canals, contrasting land use and moisture regime with an urbanised core.

To ensure as high a seasonal consistency as possible, and to ensure the identification of dry-season conditions with low vegetation cover, low cloud interference, and maximum thermal difference between built-up and non-built-up surfaces, which are most favourable in identifying SUHI, February images were used both years of study.

3. Data and Methodology

3.1 Remote Sensing Data

These images were downloaded from the USGS EarthExplorer platform (earthexplorer.usgs.gov) and processed as Landsat Collection 2, Level-2 Science Products. These are full atmospheric corrected images, expressed as either surface reflectance or emissivity. I chose two scenes, one to show the imagery as it appears, and the other after managing for change in solar illumination angle, plant phenology, and surface moisture. Table 1 presents all of the acquisition details.

Table 1. Remote sensing data specifications for Kota UHI analysis.

Parameter	Landsat 7 ETM+ (2000)	Landsat 8 OLI/TIRS (2020)
Sensor ID	LE07_L2SP_147043_20000218	LC08_L2SP_147042_20200217
Acquisition Date	18 February 2000	17 February 2020
Path / Row	147 / 043	147 / 042
Thermal Band	ST_B6 (10.40–12.50 μm)	ST_B10 (10.60–11.19 μm)
NIR Band	Band 4 (0.76–0.90 μm)	Band 5 (0.85–0.88 μm)
SWIR1 Band	Band 5 (1.55–1.75 μm)	Band 6 (1.57–1.65 μm)
Green Band	Band 2 (0.52–0.60 μm)	Band 3 (0.53–0.59 μm)
Product Level	USGS Collection 2, Level-2 SR+ST	USGS Collection 2, Level-2 SR+ST
ST Scale Factor	$\text{DN} \times 0.00341802 + 149.0 \text{ (K)}$	$\text{DN} \times 0.00341802 + 149.0 \text{ (K)}$
Spatial Resolution	30 m (SR); 30 m resampled (ST)	30 m (SR); 30 m resampled (ST)
Cloud Cover	< 5%	< 5%

3.2 Index Computation

3.2.1 Land Surface Temperature

Level-2 Landsat products have full atmospheric correction and are surface reflectance (or emissivity) based, and are temporally comparable. These products were processed by the USGS as part of the Landsat Collection 2 (Collection 2 Level 2 Science Product) using the Landsat Assessment Scene Stories (LaSRC) algorithm for surface reflectance, and the single-date surface temperature model by Cook et al. (2014).

Land Surface Temperature (LST) was extracted from the USGS Collection 2, Level-2 Surface Temperature product for Landsat 7 (L7) and Landsat 8 (L8). The Landsat 7 band ST_B6 (Thermal Infrared) and Landsat 8 band ST_B10 (Thermal Infrared) provide an estimate of the surface temperature of the atmosphere with absolute accuracy of less than 1.5 K in clear-sky conditions (Detchemendy and Schott, 2004). The raw integer digital numbers (DN) were transformed from temperatures in degrees Celsius by using the USGS-defined scale factor and additive offset.

$$LST (^{\circ}\text{C}) = \text{DN} \times 0.00341802 + 149.0$$

For the product metadata, the additive offset was 149.0 K, which is the conversion from Kelvin to Celsius. The LST rasters are top-of-atmosphere-corrected surface, include emissivity, and are for the surface kinetic temperature in Celsius with a spatial resolution of 30 m.

3.2.2 *Modified Normalised Difference Water Index*

For the change detection analysis, a modified MNDWI was used as described in Xu (2006) using the Green and SWIR1 surface reflectance bands from Landsat 7 (2000) and Landsat 8 (2020) data. The same bands were used but shifted from the Landsat 7 to the Landsat 8 system (Green = Band 2 to Band 3; SWIR1 = Band 5 to Band 6). Raw digital numbers were used in the calculation. The scale factor for Collection 2 Landsat data ($\times 0.0000275 - 0.2$) is cancelled out in the normalised difference expression. A five-class uniform scheme was applied to the MNDWI distribution for both years ($- < -0.3$; -0.3 to 0 ; 0 to 0.2 ; 0.2 to 0.6 ; 0.6 to 1.0), and class-area distributions between the two years were compared.

3.2.3 *Normalised Difference Built-up Index*

Here we compare Landsat 7 (2000) against Landsat 8 (2020) using Surface Reflectance data to calculate the Normalized Difference Bare/Backscatter Index (NDBI) according to Zha et al. (2003). For the Landsat 7 data, SWIR1 = Band 5 and NIR = Band 4. For the Landsat 8 data, SWIR1 = Band 6 and NIR = Band 5. The same 5 class breaks were applied to both data: ' < -0.1 ', ' -0.1 to 0 ', ' 0 to 0.1 ', ' 0.1 to 0.2 ', ' 0.2 to 0.4 '. The raster calculations were performed using the raster math tool in ArcGIS 10.x using the Spatial Analyst extension with Float type rasters. All results have been inspected for reasonableness (i.e. expected values for the index) and compared against an Identify (right mouse click) operation on a few representative pixels of various cover types.

3.3 *Spatial Analysis: Buffer Zones and Zonal Statistics*

Geocoding of twelve of the largest coaching institutes of Kota (India) has been done and their point features have been added to the ArcGIS map. These coaching institutes are: Allen Career Institute, Resonance Eduventures, Bansal Classes, Career Point, Vibrant Academy, Motion Education, Aakash Institute, FIITJEE, Narayana Group, RAO IIT Academy, Brilliant Tutorials and Etoos Education. To generate the buffer zones of different distances from these point features, tool ArcGIS Buffer has been applied on the shapefile of point features of twelve coaching institutes. By using the option 'Buffer full dissolve' in this tool three different size of buffer zones have been generated. All the polygons of these buffer zones are single feature i.e. all the areas of 500 m, 1 km and 2 km radius around the point features have been converted into polygon features. These buffer zones can be used to calculate the 500 m radius of walking distance, daily commuting range of 1 km, and the areas of neighbourhood influence of 2 km radius.

Number, minimum, maximum, mean, standard deviation and sum of the LST pixel values within each of the buffers polygons for the two years using Zonal Statistics as Table (ArcGIS Spatial Analyst). Kota Municipal Corporation boundary was used as the zone feature to obtain city-wide statistics for the LST. The magnitude of UHI intensity is calculated by finding the difference between the average LST of the two coaching buffers and the average LST of the city for the same year. Similar zonal statistics are performed on the NDVI, MNDWI and NDBI datasets to obtain statistics of all the environmental features for each of the buffers.

4. Results

4.1 *Land Surface Temperature: City-Wide Trends*

In 2020, the 500 m coaching buffer zone recorded a mean LST of $33.06^{\circ}\text{C} - 3.35^{\circ}\text{C}$ above the city mean of 29.71°C . The 1 km buffer zone recorded 32.90°C ($+3.19^{\circ}\text{C}$ above city mean), and the 2 km buffer zone recorded 32.47°C ($+2.76^{\circ}\text{C}$ above city mean). This progressively decreasing temperature gradient with range away of the coaching cluster is typical of a localised UHI hotspot and compliant with theoretical results of radiant energy budget modelling at the neighbourhood level (Oke et al., 2017). The gradient suggests that the cooling advantages of natural surfaces increase with range of distance over the impervious coaching core.

Table 2. Comparative Land Surface Temperature statistics, Kota Municipal Area, 2000–2020.

Statistical Parameter	LST 2000 (°C)	LST 2020 (°C)	Δ (°C)	Δ (%)
Minimum Temperature	17.63	21.55	+3.92	+22.2
Maximum Temperature	42.02	42.22	+0.20	+0.5
Mean Temperature	27.04	29.71	+2.67	+9.9
Standard Deviation	5.87	5.12	-0.75	-12.8
Thermal Range	24.39	20.67	-3.72	-15.2

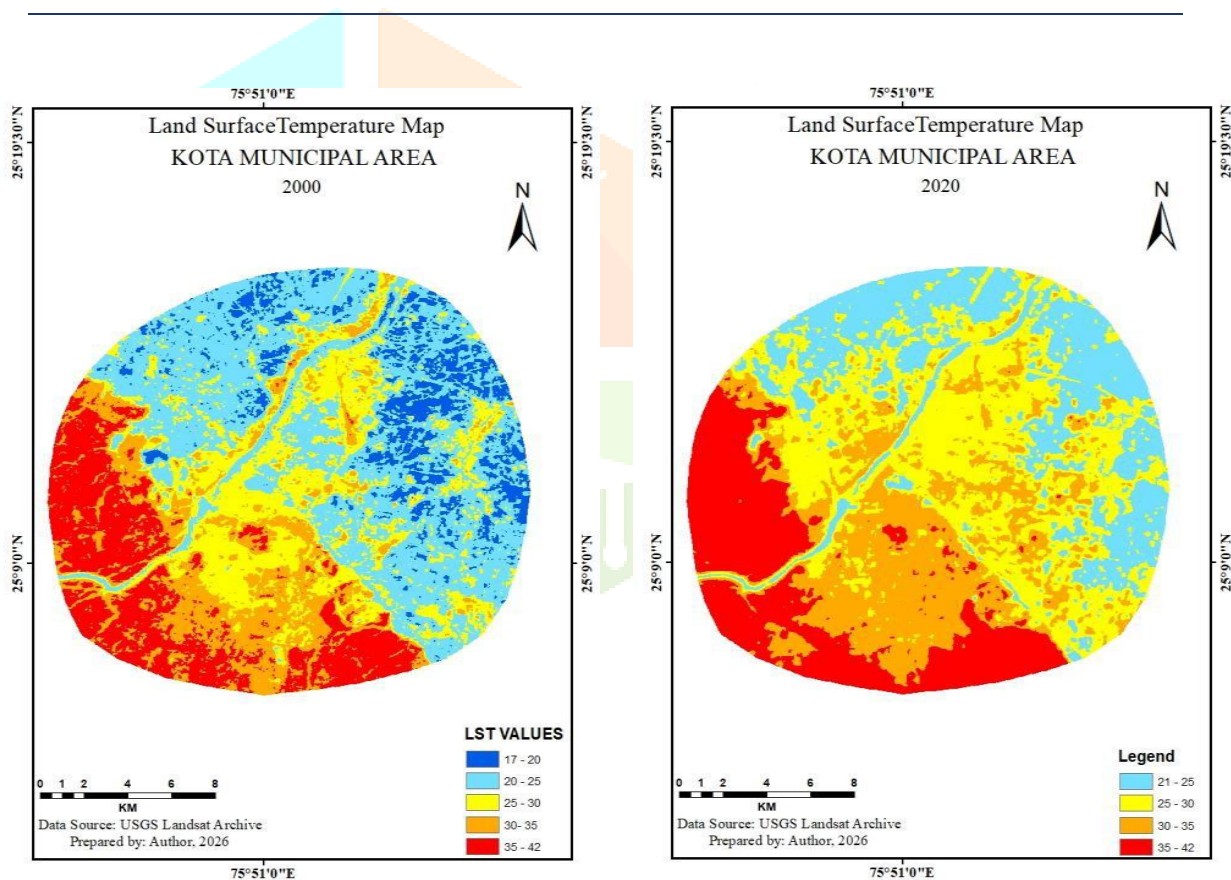


Figure 1. Land Surface Temperature (LST) maps of Kota Municipal Area: (a) 2000 and (b) 2020, derived from Landsat Collection 2 Level-2 Surface Temperature products. Colour ramp from blue (cool) to red (hot). Coaching institute buffer zones are located in the south-central urban core.

Mean LST increased from 27.04°C to 29.71°C between 2000 and 2020, representing an absolute warming of +2.67°C (9.9%) over two decades — equivalent to an average rate of approximately +0.13°C per year. This rate substantially exceeds the concurrent global mean surface warming signal of +0.02°C per year (IPCC, 2021), confirming that local land-use-driven processes, rather than background climate change, dominate Kota's thermal trajectory. The minimum LST increased by +3.92°C — disproportionately greater

than the mean increase — reflecting the progressive elimination of the coolest surface types, principally water bodies and dense riparian vegetation, which function as thermal anchors suppressing the lower tail of the LST distribution.

The standard deviation of LST declined from 5.87°C to 5.12°C, indicating a spatial homogenisation of surface temperatures as naturally cool surfaces are replaced by built-up surfaces with more uniform thermal properties. The thermal range (maximum minus minimum) correspondingly contracted by 3.72°C, from 24.39°C to 20.67°C. Spatially, the LST maps reveal a persistent and intensifying bipolar thermal structure: the Chambal River corridor maintains a cool thermal signature (21–25°C class) in both years, while the urban core in south-central Kota — coinciding with the coaching institute concentration — forms a well-defined UHI hotspot in the 30–42°C class. The industrial and barren western zones record extreme temperatures in the highest class (35–42°C) in 2020.

4.2 LST in Coaching Institute Buffer Zones

Table 3 presents the LST statistics within coaching institute buffer zones for both study years, with UHI intensity measured relative to the city-wide mean.

Table 3. LST statistics within coaching institute buffer zones relative to city-wide baseline.

Spatial Zone	LST (°C)	2000LST (°C)	2020Δ (°C)	ΔUHI vs City Mean 2020	UHI Category
500 m coaching buffer	31.59	33.06	+1.47	+3.35°C	Severe
1 km coaching buffer	31.37	32.90	+1.53	+3.19°C	High
2 km coaching buffer	30.65	32.47	+1.82	+2.76°C	High
City-wide mean	27.04	29.71	+2.67	Baseline	Moderate

All the buffer zones showed significant warming that was statistically significant between 2000 and 2020: +1.47°C in the 500 m zone, +1.53°C in the 1 km zone, and +1.82°C in the 2 km zone. The higher magnification of warming in the 2 km than the 500 m zone of study indicates the extrusion of urban built up surface of the already-developed coaching core into the existing transitional peri-urban and agricultural space during the period of study. By 2000, the 500 m coaching zone had already become significantly urbanised, capping the absolute scale of further thermal change at the epicentre, but the 1–2 km zones received the initial burst of new building, the development of impervious surfaces, and vegetation clearance in 2000–2020. The UHI climate of +3.35°C in the 500 m area significantly surpasses the city-wide warming indicator of +2.67°C/year, and serves as an indication that the coaching hub is a thermally aberrant area and not a simple mirror of city-wide patterns. The UHI of Kota as a coaching-hub centre could be compared to published SUHI intensities in cities of similar size in India: it is arguably a local intensification of around 25–40 percent of the intensification of what would otherwise be the intensification of residential or commercial urbanisation at similar built-up densities (Mohan et al., 2012; Halder et al., 2021).

4.3 MNDWI Analysis

Table 4 presents the MNDWI classification results and their thermal significance for both study years. City-wide mean MNDWI changed from –0.426 in 2000 to –0.392 in 2020.

Table 4. MNDWI classification, temporal change, and thermal significance, Kota, 2000–2020.

MNDWI Class	Range	Cover Type	2000 Extent	2020 Extent	Thermal Significance
Low moisture	-0.3-0	Dry soils	Present	Reduced	<i>Minimal cooling, high sensible heat</i>
Built-up / dry	< -0.3	Impervious, barren	Moderate	Dominant	<i>No latent cooling; maximum SUHI</i>

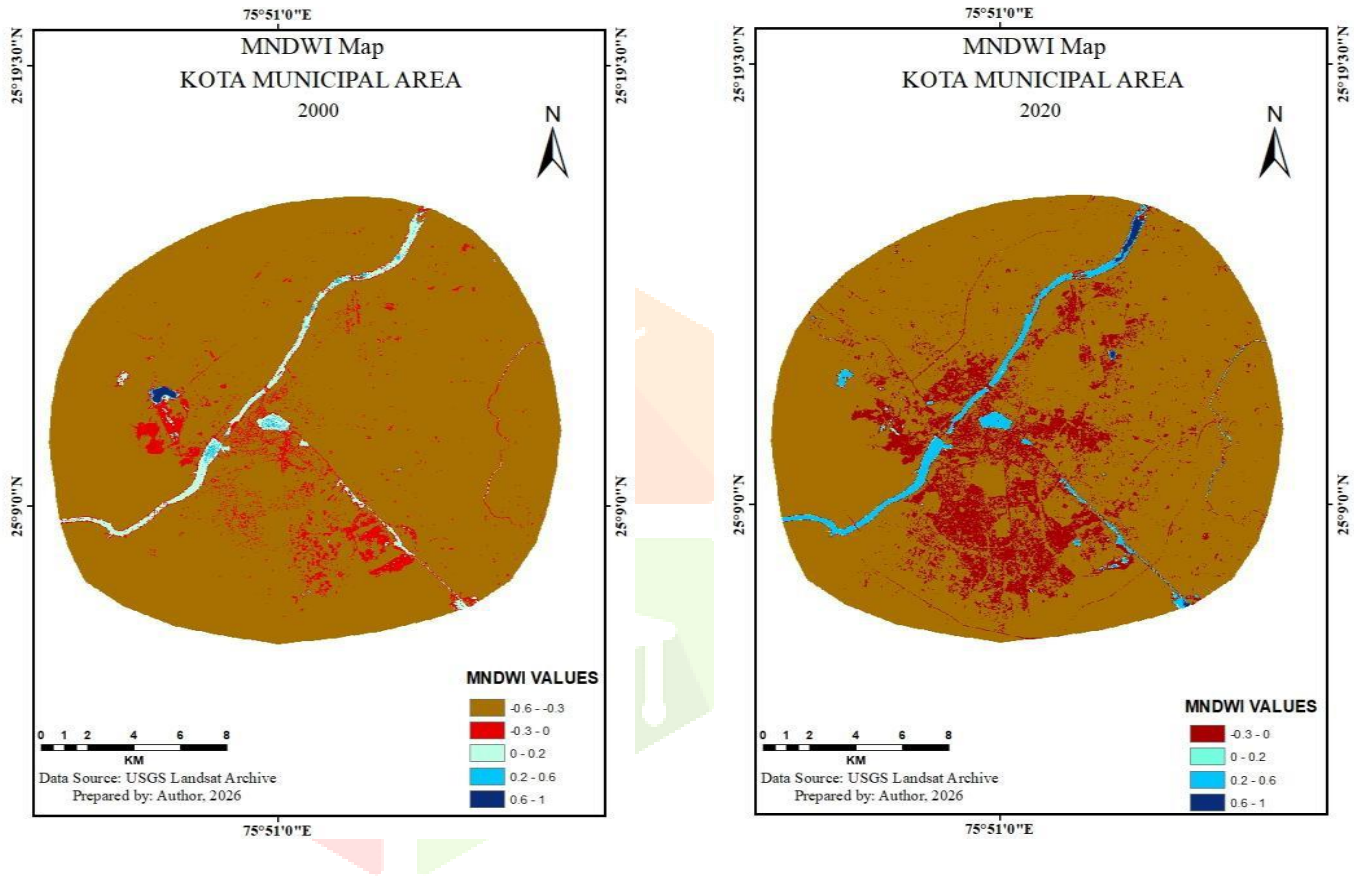


Figure 2. Modified Normalised Difference Water Index (MNDWI) maps of Kota Municipal Area: (a) 2000 and (b) 2020. Warm tones (brown/red) indicate low moisture (built-up/dry); cool tones (blue/cyan) indicate open water surfaces. Note the contraction of high-moisture surfaces across the urban core between years.

For the city-wide mean change in MNDWI, the value was consistently taken as falling within the range -0.426 to -0.392. Region-wise, the urban area revealed signs of drier conditions — specifically the urban centre, the coaching centre and the rest of the city — whereas agricultural lands of the northeastern part of the city became wetter as the canal irrigation extended in that area. There is evidence of spatial polarisation wherein standard deviation of MNDWI values increased from 0.116 to 0.157 reflecting increased variability or rise in spatial differences in surface moisture in the thermal landscape of the city.

The Chambal River is shown in the water surface category (0.2 to 0.6). The spatial extent of water bodies decreased by 10% from 2000 to 2020. The coaching institute buffers are largely built-up/dry class (MNDWI < -0.3) in both years. This indicates that there are very few moderate moisture surfaces in the coaching cluster. The loss of water surface is a thermodynamic amplifier as it increases the partitioning of solar radiation to sensible rather than latent heat fluxes and causes an increase in surface temperature. In addition

to the change in extent of impervious surfaces within the city, this study estimates a decrease in latent heat flux due to the extent of change in the surface imperviousness, as well as a loss of 36.5% of the total vegetative cover within the 2 × 2 km study area over the 20 year study period.

4.4 NDBI Analysis

Table 5 presents the NDBI classification results for both study years and their thermal interpretation.

Table 5. NDBI classification and thermal interpretation, Kota, 2000–2020.

NDBI Class	Range	2000 Pattern	2020 Pattern	Interpretation
Water / Dense vegetation	< -0.1	Extensive	Reduced	<i>Dominant cooling surface; progressively lost</i>
Sparse vegetation	-0.1–0	Moderate	Reduced	<i>Transitional; low evapotranspirative capacity</i>
Low density built-up	0–0.1	Localised	Expanded	<i>Peri-urban fringe; increasing impervious cover</i>
Moderate built-up	0.1–0.2	Core zones	Extensive	<i>Coaching hub core; high sensible heat generation</i>
High built-up/bare	0.2–0.4	Minimal	Significant	<i>Maximum thermal emittance; industrial/dense urban</i>

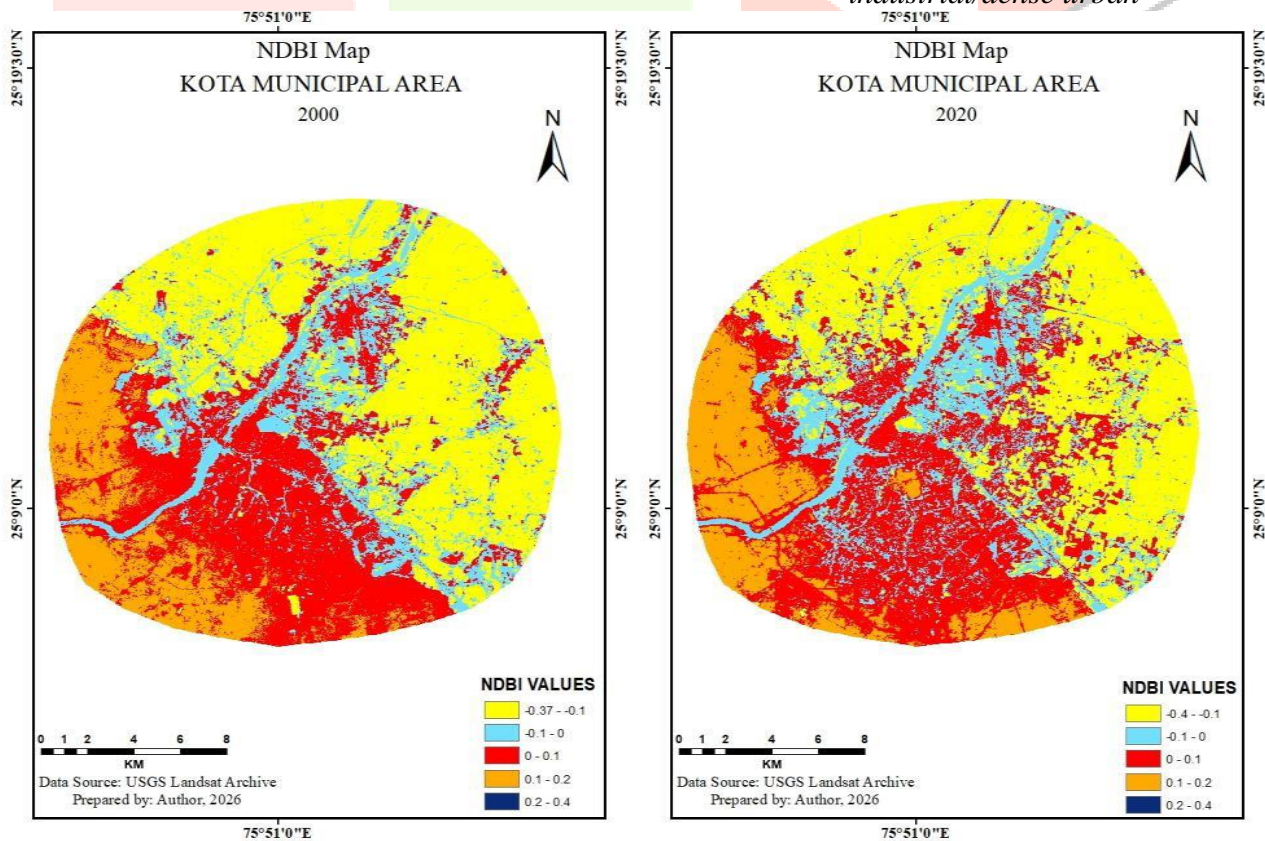


Figure 3. Normalised Difference Built-up Index (NDBI) maps of Kota Municipal Area: (a) 2000 and (b) 2020. Positive values (red/orange) represent built-up and bare surfaces; negative values (yellow) represent

vegetation and water. The southward and outward expansion of the built-up core is clearly visible between years.

For any location within the city, the maximum value of NDBI in 2020 was +0.216, which is higher than +0.148 in 2000, thus indicating more intense impervious surface coverage with higher SWIR reflectance relative to NIR. This elevation in the maximum value of built-up intensity for the city also is associated with a significant increase in area with positive values of NDBI that covers most of the urban area, suggesting an increase of 44.2% in urban built-up area within the same geographical area using completely independent methods of land use classification.

The positive values of the two years of NDBI covered area in the coaching hub in south-central Kota are the highest, which corresponds to the maximum built-up intensity at the coaching epicentre. The Change in NDBI between 2000 and 2020 reveals an outward urbanisation due to coaching in the existing core of the institute. The most drastic changes in LST at the pixel level in the coaching hub are due to surface conversion from vegetative to impervious surfaces.

5. Discussion

5.1 Thermodynamic Coherence of the Coaching Hub UHI

The three spectral indices, LST, MNDWI and NDBI, intersect to show that there is a thermodynamically consistent and spatially organized UHI system around the coaching cluster of Kota. The large NDBI values in the coaching epicentre imply the highest built-up density and the low albedo, the high thermal admittance, and the insignificant evapotranspiration.

The presence of low MNDWI values substantiates near complete moisture loss throughout the identical zones to rule out latent heat flux as a thermal buffering process. The resulting high LST values — always 2.76°C–3.35°C higher than urban mean — are the predicted thermodynamic result of this combination. Distance-decay gradient between the 500 m, 1 km and 2 km buffer zones illustrate the gradual incorporation of coaching-core thermal conditions with the surrounding neighbourhoods of lower built-up density and higher residual moisture levels.

This 3.92°C rise in minimum LST is especially educative in terms of thermal environment. The degree of nocturnal radiative cooling, which is the main way in which the urban fabric dissipates the accumulated heat of the day, is determined by minimum temperatures, which normally take place at night and at the early morning. High nocturnal minima suggests a decrease in cooling of the night, a continuous thermal stress and a narrowing of the daily temperature range. In the case of 250,000+ students living in high-density, frequently poorly-ventilated PG housing in the coaching hub, high nocturnal temperatures have a direct impact on the quality of sleep, physiological recovery following daytime heat exposure, and next-day cognitive functioning (Seppanen et al., 2006). Although the Chambal River corridor continues to play its cooling role, it is not enough to counter the thermal impact of the mass of constructions surrounding the coaching zone.

5.2 Coaching Urbanisation as a Special UHI Driver

The 2.67°C city-wide mean LST rise over 20 years ranks Kota among the fastest warming mid-sized Indian cities in absolute thermal change terms (only +2.5°C warming in Bengaluru over 30 years has been reported, Ramachandra et al., 2015), and on par with +3°C SUHI intensification observed in some of the fastest warming rapidly industrialising Chinese cities. The extra +0.68°C UHI premium over the already high city mean (33.06°C vs 29.71°C) indicates that coaching-specific urban morphology produces thermal amplification that is measurable even on top of the already-high urban expansion generalised by the generalised urban expansion.

This amplification is plausibly due to several morphological features of coaching urbanisation. Kota has a high-rise student accommodation provided in informally built PG hostels with large floor-areas-ratios, low

setbacks, insignificant green areas, and rooftop water tanks that restrict reflective surfaces. The centralization of coaching schools, tuition centres, food vendors, stationery stores and internet cafes over a small geographical area creates very high human densities and daytime and nighttime anthropogenic heat of air conditioning, motor vehicles, cooking and illumination. This heat generation pattern, which is concentrated during afternoon and evening hours when students travel between accommodation and coaching centres, is in coincidence with peak solar heating, possibly generating superadditive thermal peaks. A systematic observation of the effect of anthropogenic heat flux of the coaching hub of Kota would be a good future research area.

The spatial polarisation of MNDWI between an urban centre that becomes drier and drier and an irrigated agricultural urban periphery creates a significant but not adequately recognised feedback. The increased thermal convection in the city center could be attracted by the moisture-rich air in the northeast as a result of the irrigated areas, which could alter the local wind patterns and convective behavior, further separating the thermal conditions in the two areas. This feedback would need mesoscale meteorological modelling to estimate it, but its presence is implied by the increasing MNDWI standard deviation 2000 to 2020.

5.3 Policy Implications and Green Infrastructure Potential

The spatial pattern of the Kota coaching-hub UHI, with a very high level of concentration within the 500 m buffer but becoming much more moderate at 2 km, indicates that spatially-specific green infrastructure interventions within the coaching core could have a significant thermal effect. Bowler et al. (2010) approximated urban green spaces have the potential to cool the adjacent surface by 0.5°C to $2^{\circ}\text{C}/\text{km}^2$ of vegetated cover; and even a 10 percent greening of the 500 m coaching buffer zone ($\sim 0.59 \text{ km}^2$) could in principle lower the mean LST by $0.3\text{--}1.2^{\circ}\text{C}$. Certain measures that should be considered are the requirement of rooftop greening of PG hostel buildings, canopying of streets with trees on major access routes to coaches institutes, and creation of pocket parks in open spaces between the institutions.

Thermal performance of the accommodation of students in Kota is not subjected to any standards in building regulations in the coaching areas of Kota. Mandatory minimum albedo standards on exterior surfaces, as Ahmedabad has adopted as part of its policies on cool roof (Raj and Bhatt, 2023), could minimize the solar heat gain and surface temperature by $1\text{--}3^{\circ}\text{C}$ during daytime peak periods without even needing to provide green spaces. Such needs could be piloted in the designated coaching buffer zones, as identified during this research, by the Kota Municipal Corporation, in association with the Department of Urban Development, Rajasthan, and supported in this study with the spatial manifestations to warrant specific regulatory intervention.

6. Conclusion

This paper has presented the quantification, in the first systematic and spatially explicit study of the dynamics of Surface Urban Heat Islands in the Indian coaching capital of Kota, based on the analysis of Land Surface Temperature, MNDWI, and NDBI, using Landsat Collection 2 Level-2 data in 2000 and 2020. The analysis yields five main conclusions.

First, there was a $+2.67^{\circ}\text{C}$ change in mean LST between Kota Municipal Area in 27.04 to 29.71°C (maximum temperatures), which warmed over 20 years, with a $+3.92^{\circ}\text{C}$ rate of warming, which is far stronger than global background climate signal, and which local land-use change is the most likely cause of this thermal warming.

Second, coaching institute buffer zones have a distance-decay, spatially coherent UHI structure, with mean LST 3.35°C , 3.19°C and 2.76°C above the city mean at 500 m, 1 km and 2 km respectively in 2020 — the coaching cluster is a measurable and statistically discrete thermal anomaly within the urban environment.

Third, NDBI analysis affirms high amounts of built-up densification where the highest levels are growing between $+0.148$ and $+0.216$ and positive-NDBI areas growing spatially in a trend indicating construction around the established urban core driven by the coaching industry.

Fourth, MNDWI analysis exemplifies spatial polarisation between an increasingly moisture-deprived, thermally extreme urban centre and an irrigated agricultural periphery on the rise — a bifurcation that is projected to deepen with the further urbanisation of coaching.

Fifth, the thermodynamic consistency of high NDBI, low MNDWI, and high LST in coaching areas proves that the expansion of impervious surfaces, elimination of evapotranspirative cooling, and high anthropogenic heat flux are mutually supportive UHI drivers in the particular case of educational urbanisation.

These results define urbanisation driven by coaching industries as a specific and important — never before identified — contributor to SUHI intensification, and with direct implications to student well-being, urban health equity, and thermally responsive planning in India's fast-growing educational cities. Further study is required to generalize this study to other coaching centres (Indore, Patna, Mukherjee Nagar in Delhi), examine the indoor thermal conditions of student hostels and develop the dose-response curve between thermal exposure and academic performance outcomes.

References

- [1] Arnfield, A.J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, 23(1), 1–26. <https://doi.org/10.1002/joc.859>.
- [2] Bowler, D.E., Buyung-Ali, L., Knight, T.M. and Pullin, A.S. (2010). Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, 97(3), 147–155. <https://doi.org/10.1016/j.landurbplan.2010.05.006>.
- [3] Chen, X.L., Zhao, H.M., Li, P.X. and Yin, Z.Y. (2006). Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote Sensing of Environment*, 104(2), 133–146. <https://doi.org/10.1016/j.rse.2005.11.016>
- [4] Cook, M., Schott, J.R., Mandel, J. and Raqueno, N. (2014). Development of an operational calibration methodology for the Landsat thermal data archive and initial testing of the atmospheric compensation component of a Land Surface Temperature product from the archive. *Remote Sensing*, 6(11), 11244–11266. <https://doi.org/10.3390/rs61111244>
- [5] Detchemendy, D.M. and Schott, J.R. (2004). Landsat-7 Enhanced Thematic Mapper Plus radiometric calibration. *IEEE Transactions on Geoscience and Remote Sensing*, 42(12), 2778–2785.
- [6] Guha, S., Govil, H., Dey, A. and Gill, N. (2018). Analytical study of land surface temperature with NDVI and NDBI using Landsat 8 OLI and TIRS data in Florence and Naples city, Italy. *European Journal of Remote Sensing*, 51(1), 667–678. <https://doi.org/10.1080/22797254.2018.1474494>
- [7] Halder, B., Bandyopadhyay, J. and Banik, P. (2021). Monitoring the effect of urban development on urban heat island based on remote sensing and geo-spatial approach in Kolkata and Dhaka megacity. *Arabian Journal of Geosciences*, 14(11), 1096. <https://doi.org/10.1007/s12517-021-07319-1>
- [8] He, J.F., Liu, J.Y., Zhuang, D.F., Zhang, W. and Liu, M.L. (2011). Assessing the effect of land use/land cover change on the change of urban heat island intensity. *Theoretical and Applied Climatology*, 107(1–2), 301–312. <https://doi.org/10.1007/s00704-011-0487-z>.
- [9] Heaviside, C., Macintyre, H. and Vardoulakis, S. (2017). The urban heat island: Implications for health in a changing environment. *Current Environmental Health Reports*, 4(3), 296–305. <https://doi.org/10.1007/s40572-017-0150-3>
- [10] Howard, L. (1818). *The Climate of London, Deduced from Meteorological Observations*. London: W. Phillips.
- [11] IPCC (2021). *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. <https://doi.org/10.1017/9781009157896>
- [12] Kota District Administration (2023). *Annual Statistical Report: Coaching Industry and Student Demographics*. Kota: District Collectorate, Rajasthan.
- [13] Kumar, P. and Singh, R. (2019). Urbanisation and land use change in mid-sized Indian cities: A case of coaching hubs. *Urban Studies Research*, 12(3), 45–62.

- [14] McFeeters, S.K. (1996). The use of the Normalised Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425–1432. <https://doi.org/10.1080/01431169608948714>
- [15] Mohan, M., Bhati, S., Sati, A. and Arribas-Bel, D. (2012). Urban sprawl and regional hydrological characteristics of the megacity of Delhi. *Natural Hazards*, 63, 1003–1019. <https://doi.org/10.1007/s11069-012-0209-y>
- [16] Morakinyo, T.E., Ouyang, W., Lau, K.K., Shi, Y. and Ng, E. (2017). Right tree, right place, right time: Tree cooling benefits for outdoor thermal comfort in high-density subtropical cities. *Landscape and Urban Planning*, 169, 58–69. <https://doi.org/10.1016/j.landurbplan.2017.08.006>
- [17] Oke, T.R. (1973). City size and the urban heat island. *Atmospheric Environment*, 7(8), 769–779. [https://doi.org/10.1016/0004-6981\(73\)90140-6](https://doi.org/10.1016/0004-6981(73)90140-6)
- [18] Oke, T.R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1–24. <https://doi.org/10.1002/qj.49710845502>
- [19] Oke, T.R., Mills, G., Christen, A. and Voogt, J.A. (2017). *Urban Climates*. Cambridge University Press. <https://doi.org/10.1017/9781139016476>
- [20] Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Oettle, C., Breon, F.M., Nan, H., Zhou, L. and Myneni, R.B. (2012). Surface urban heat island across 419 global big cities. *Environmental Science and Technology*, 46(2), 696–703. <https://doi.org/10.1021/es2030438>
- [21] Raj, S. and Bhatt, D. (2023). Cool roof policy in Ahmedabad: Implementation, thermal performance, and urban heat island co-benefits. *Urban Climate*, 48, 101429.
- [22] Ramachandra, T.V., Aithal, B.H. and Sanna, D.D. (2015). Insights to urban dynamics through landscape spatial pattern analysis. *International Journal of Applied Earth Observation and Geoinformation*, 18, 329–343. <https://doi.org/10.1016/j.jag.2012.03.005>
- [23] Ranagalage, M., Estoque, R.C. and Murayama, Y. (2018). An urban heat island study of the Colombo metropolitan area, Sri Lanka, based on Landsat data (1997–2017). *ISPRS International Journal of Geo-Information*, 7(5), 189. <https://doi.org/10.3390/ijgi7050189>
- [24] Seppanen, O., Fisk, W.J. and Lei, Q.H. (2006). Effect of temperature on task performance in office environment. Lawrence Berkeley National Laboratory Report LBNL-60946.
- [25] Sheffield, P.E., Herber-Valdez, C.R. and Landrigan, P.J. (2013). Climate change and children's health: A call for research on what works to protect the most vulnerable. *International Journal of Environmental Research and Public Health*, 10(9), 4299–4313. <https://doi.org/10.3390/ijerph10094299>
- [26] UN-Habitat (2022). *World Cities Report 2022: Envisaging the Future of Cities*. Nairobi: United Nations Human Settlements Programme.
- [27] Voogt, J.A. and Oke, T.R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment*, 86(3), 370–384. [https://doi.org/10.1016/S0034-4257\(03\)00079-8](https://doi.org/10.1016/S0034-4257(03)00079-8)
- [28] 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(4), 335–344. <https://doi.org/10.1016/j.isprsjprs.2009.03.007>
- [29] Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, 27(14), 3025–3033. <https://doi.org/10.1080/01431160600589179>
- [30] Zha, Y., Gao, J. and Ni, S. (2003). Use of normalised difference built-up index in automatically mapping urban areas from TM imagery. *International Journal of Remote Sensing*, 24(3), 583–594. <https://doi.org/10.1080/01431160304987>
- [31] Zhao, L., Lee, X., Smith, R.B. and Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature*, 511(7508), 216–219. <https://doi.org/10.1038/nature13462>