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Spatio-Temporal Analysis of Urban Heat Island Using Remote Sensing and GIS in Lucknow City, Lucknow District, U.P. (2002-2020)

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Abstract

An Urban Heat Island (UHI) is a metropolitan phenomenon. The morphological character of a dynamic city creates pockets in an urban area that are significantly warmer than its surrounding urban and peripheral rural areas. The causes for the creation of UHI vary globally but the core sources are due to industrialisation, urbanisation and varied anthropogenic activities.

The urban area of the city of Lucknow has been expanding rapidly in the past decades. In this study ARC GIS 10.5 and QGIS 3.18 softwares were used to obtain the effect of UHI which is analysed using Landsat 4-5 TM, Landsat 7 ETM+ and Landsat 8 OLI/TIRS data in the period of 2002–2020 in Lucknow City. A mono window algorithm was applied to retrieve the Land Surface Temperature (LST) distribution from the Landsat 4-5 TM, Landsat 7 ETM+ and Landsat 8 OLI/TIRS data and UHI Intensity was calculated between the LST of urban and rural points. Google Earth Pro was used identify the 5 areas classified in the LULC classification.

Land Use/Land Cover (LULC) was calculated on the same data using supervised classification with the help of Maximum Likelihood classifier (MLC) statistical tool, reclassify tool and raster to polygon tool. Linear regression analysis was used and scatter plots were developed to calculate the correlation between Land Surface Temperature (LST) and the Normalised Difference Vegetation Index (NDVI) which was calculated to check the impacts of the green areas on the urban heat island and the correlation between LST and the Normalised Difference Build-up Index (NDBI) was also calculated which was analysed to explore the impact of the built-up area on the urban heat island.

The results indicate that the effects of the Urban Heat Island (UHI) in Lucknow City are felt in many urban pockets. The UHI intensity shows that there is a wide difference in temperature between 8 urban location and 8 rural locations in the study area. UHI intensities from remotely sensed data show that the study area reflects a maximum temperature of 34.1°C and a minimum temperature of 29.54°C which is 4.56°C warmer than rural areas over an 18-year period from 2002 to 2020. The negative correlation between LST and NDVI indicates that the green area can reduce the effect of the urban heat island such as found in Kukrail forest, dense forest on western side, Badi Jugauli Forest, Lohia Park, Janeshwar Mishra Park etc. while the positive correlation between LST and NDBI means that the built-up land use can increase the effect of the urban heat island in a given urban region.

The future sprawling of the study area should be more holistic where human welfare should be first prioritised. Various relevant mitigation strategies are proposed for the study area in order to combat increasing urban heat at the local level in order to achieve Lucknow as a smart and sustainable city.

Keywords: urban heat island, land surface temperature, normalised difference vegetation index, normalised difference build-up Index.

1. Introduction

The term "urban heat island" refers to the observed temperature difference between urban environments and the surrounding rural areas. The process of urbanisation can increase local temperatures in comparison to less built-up suburban or rural areas, creating an urban heat island (UHI).

According to United Nations Climate Change the Earth is now about 1.1°C warmer than it was in the late 1800s and the last decade (2011-2020) was the warmest on record. Moreover, urban areas are more vulnerable to heat, however, because the amount of warming caused by global climate change is compounded by the urban heat island effect. This means that people who live in cities are going to face higher temperatures and stronger heat waves in the future

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as climate warms. More than half the global population lives in urban areas today and by the year 2050, the percentage of urban dwellers worldwide is expected to reach 68%, so the problem of urban heat islands will continue to grow. Thus, reducing urban heat islands can help in reducing climate change.

Also, studies of rapidly growing cities globally also indicate an increased LST, which usually forms an urban heat island due to the dramatic changes in land use linked with urbanization. This growth has also contributed to high energy demand that affects human health due to air pollution and greenhouse gas (GHG) emissions. Therefore, the study of LULC changes and their influence on surface UHI using land surface temperature is crucial in implementing policies and strategies aimed at mitigating the negative impacts of urban growth due to rapid urbanization.

The increase in the urban heat island problem has been a common phenomenon in Indian cities due to the rapid haphazard urbanisation after the implementation of new economic policy in 1990's which accelerated during 2002-2020. According to the World Bank, presently, 35% of the Indian population are urban. In India, according to the 1901 census, there were 1,830 UAs/Towns where the population residing was 10.84%, which increased to 31.16% urban population residing in 7,935 UAs/Towns by the 2011 census.

Lucknow is the capital city of Uttar Pradesh. It is among the largest metropolitan cities in India and has one of the fastest growing economies and industrial growth. So, the outcome of this growth is the tremendous changes in land use and land cover (LULC) pattern. The alteration and encroachment of the same has led to the formation of surface urban heat island (UHI). Therefore, land use and land cover change dynamics are crucial factors influencing surface UHI in the Lucknow City.

2. Objectives of the study

The objective of the study is to assess the Urban Heat Island in Lucknow City.

3. Study Area

The Lucknow City which is the study area is located between 80.65°E to 81.09°E longitude and 26.65°N to 27.01°N latitude (Figure No. 1). It has an aerial extent of 981.7 km². Lucknow city is surrounded by rural tehsils like Malihabad, Kakori, Mohanlalganj, Gosainganj, Chihat, and Itaunja. Lucknow lies in the Middle Ganga basin with flat alluvial terrain and is covered with a thick pile of Quaternary sediments, uncomfortably overlying the basement of Bundelkhand Granitoids and sedimentary rocks of the Vindhyan Supergroup. Lucknow has been placed in the zone of moderate intensity earthquakes (zone III). The Lucknow city lies at an average altitude of 110 meters above mean sea level and generally slopes to the east. The Gomti river meanders for another 12 km through the middle of the state capital and flows through the city, serving as a bed for agriculture and dividing the city into two regions, namely Trans-Gomati and Cis-Gomati. The Lucknow City has a warm humid subtropical climate with cool dry winter from December to February and dry, hot summer from April to June. In winter the maximum temperature is around 27°C (77°F) and the minimum temperature of 3°C (37°F) to 7°C (45°F). Fog is quite common from late December to late January. Summers are extremely hot with temperatures ranging from 40°C (104°F) to 45° C (113°F). The Rainy Season is from mid-June to mid-September, when Lucknow gets an average of 896.9 millimetres (35.28in) from south-west monsoon winds, and occasionally frontal rainfall will occur in January. As per provisional reports of Census India Lucknow city has population of 2,817,105; its urban / metropolitan population is 2,902,920 out of which 1,509,451 are males and 1,393,469 are females.

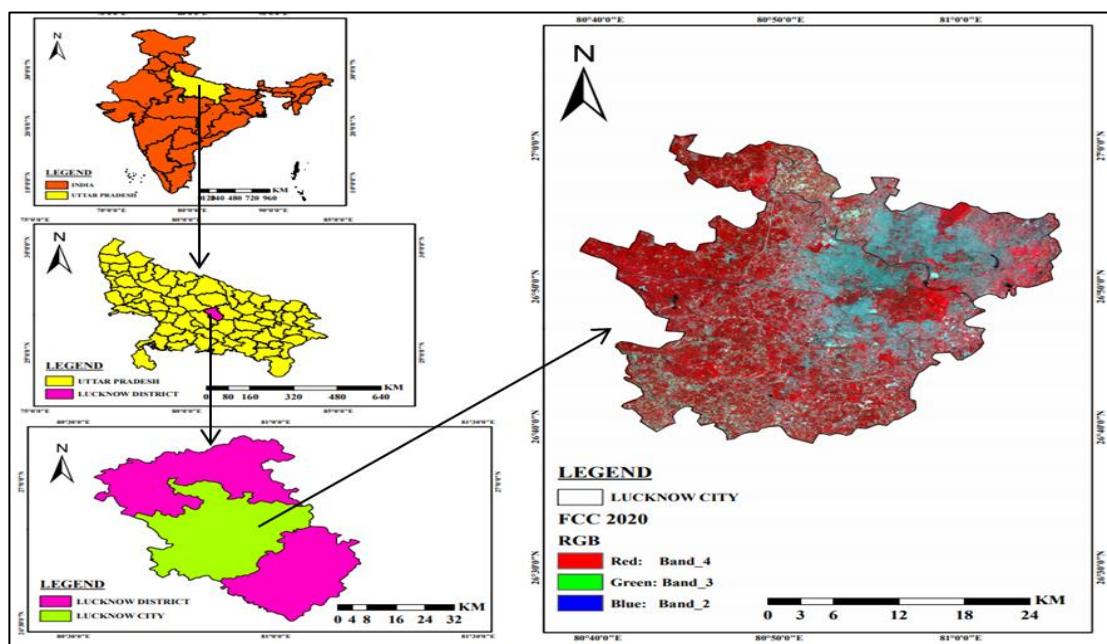


Fig. 1: Study Area.

4. Methodology

4.1. Data Collection

This study is based on mainly secondary data.

4.1.1. Satellite Data: In this study, daytime Landsat satellite imagery as given in (Table No. 1) is used for the spatiotemporal patterns of Land Surface Temperature

(LST), Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), and Land Use/Land Cover (LULC). Available satellite images during the period of September and October were acquired from the United State Geological Survey (USGS) website freely in GEOTIFF Format. Multi temporal images of Landsat satellite images have UTM Figure map projections with

WGS84 data and zone as 44N.

- Landsat 8 OLI/TIRS, which has a 30-metre resolution and nine spectral bands.
- Landsat 7 ETM+, which has a 30-metre resolution and eight spectral bands.
- Landsat 4-5 TM, which has a 30-metre resolution and eight spectral bands.

Table 1: Satellite Data used 2002,2010 and 2020.

Sr. No.	Date	Landsat Series	Time	WRS Row	WRS Path	Cloud Cover	Band Combination
1	September 30, 2002	Landsat 7 ETM+ C1 Level -1	04:54:37	041	144	0.00	4,3,2
2	September 28, 2010	Landsat 4-5 TM C1 Level -1	04:56:59	041	144	1.00	4,3,2
3	October 09, 2020	Landsat 8 OLI/TIRS C1 Level -1	05:07:13	041	144	1.00	5,4,3

4.1.2. Shape File - The shape file of Lucknow City has been extracted from **Diva GIS** from administrative boundaries freely.

4.1.3. Google Maps - Different urban and suburban points

were taken across the study area with the aid of Google Maps in order to know where precisely the Urban Heat Island was prominent.

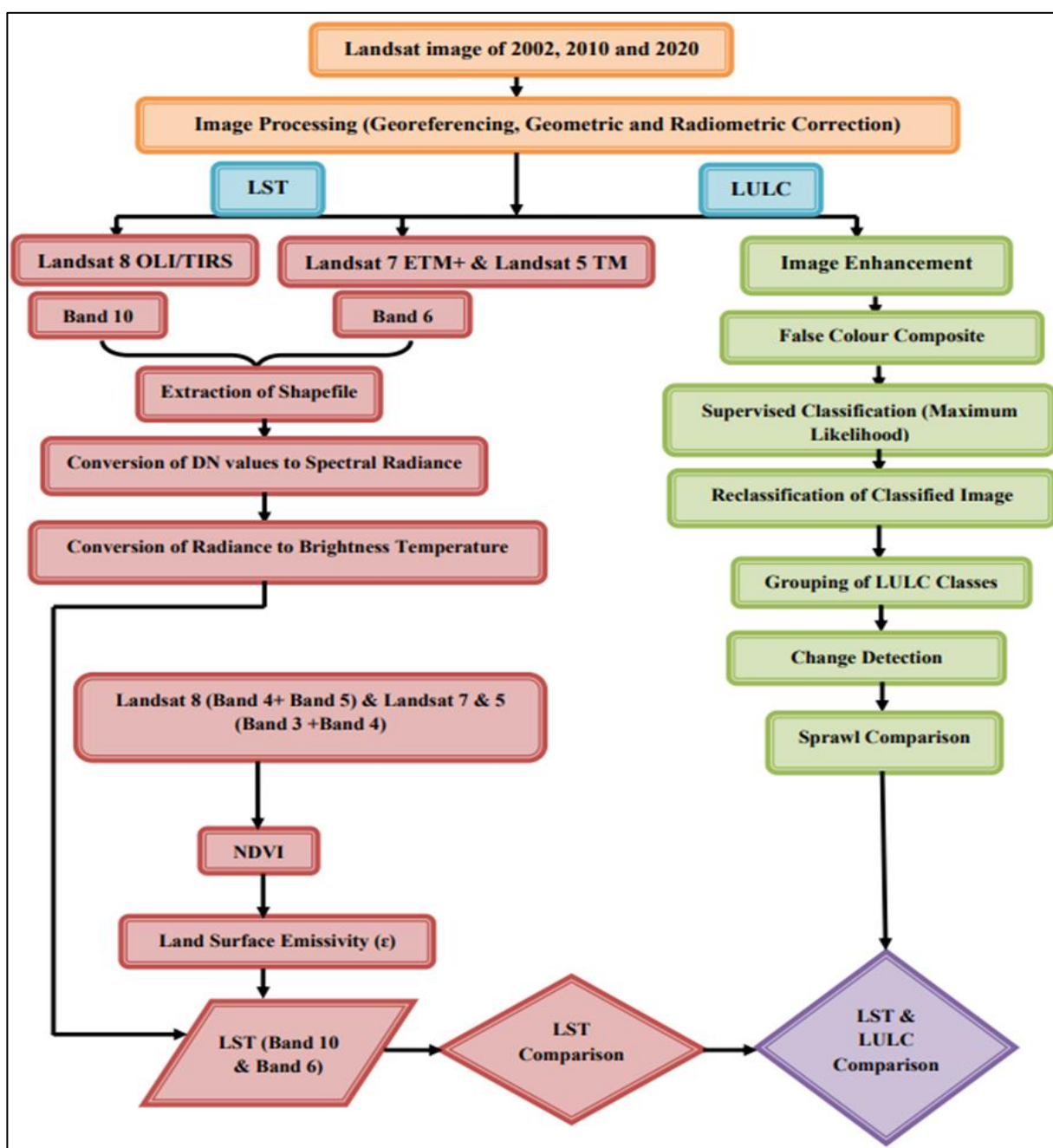


Fig. 2: Methodology of Land Surface Temperature (LST) and Land use/ Land Cover (LULC).

4.2. Methods

To achieve the objective of this study, we followed three broad methods.

- a) The first method involved obtaining the LULC classification.
- b) The second method is to generate thermal band Land Surface Temperatures (LST).
- c) The third method is to extract NDVI and NDBI.

All these methods were done using ArcGIS 10.5 and QGIS 3.18. The detailed methods of the study are given in the following section.

4.2.1. Image Pre-processing: The temporal satellite imagery of 2002, 2010 and 2020 from the Landsat Series was first georeferenced in the same co-ordinate system as the shapefile. These images were further geometrically and radiometrically corrected to enhance their quality and achieve better results.

4.2.2. Land Use/ Land Cover (LULC) Classification

With the help of ARCGIS 10.5 and QGIS 3.18 software, supervised classification has been used for the process of image classification for 2002, 2010, and 2020 imagery. The classifications of the images were done for three years to find the spatial changes concerning time over the years 2002, 2010 and 2020.

- Firstly, the images are layer stacked, and then the image enhancement methods are performed on the raster images for better pixel quality. This improved image was then clipped for the required study area of Lucknow City. The bands are then combined with the help of the composite band tool to create a single Natural Colour Composite image.
- This image was further changed into a False Colour Composite (FCC) by using a band combination of Band 4, 3, and 2 for Landsat 7 and Landsat 5. Also, Band 5, 4, and 3 was used for Landsat 8. The FCC of 2002, 2010, and 2020 was classified with the help of Google Earth Pro, to assign training areas of different features to be classified.
- The Maximum Likelihood classifier (MLC), a statistical tool in which the pixels are assigned based on the class of maximum probability, was used to classify the image into 5 classes namely, water, urban built-up, vegetation, agriculture, and barren land (Table No. 2) These categorised images were further reclassified with the help of the Reclassify tool.
- Further, the reclassified images were converted into polygons with the help of the raster to polygon tool. Furthermore, the area for each class was calculated in the attribute table. The changes in the LULC over the years were then detected.

Table No. 2: Land Use/ Land Cover (LULC)classification categories.

Sr. No.	No. Of Classes	Color Used
1	Water	Dark Blue
2	Urban Built-Up	Red
3	Vegetation	Dark Green
4	Agriculture	Light Green
5	Barren Land	Yucca Yellow

4.2.3. Land Surface Temperature (LST) Formation: The temperature of the earth’s surface is known as Land Surface Temperature (LST). The Landsat 4-5 TM Thermal

Band 6 (10.40-12.50 μm), Landsat 7 ETM+ Thermal Band 6 VCID 1 (10.4 – 12.5 μm) and Landsat 8 OLI/TIRS Thermal Band 10 (10.60 -11.19 μm) has a spatial resolution of 120 metres, 60 metres and 100 metres respectively which are considered suitable for capturing the multifaceted intra-urban temperature differences thus makes it effective for urban climate analysis. The calculation of Land Surface Temperature (LST) is done with the help of raster calculator tool in ARCGIS 10.5 software used in the image of 2002, 2010 and 2020 using the following steps:

4.2.3.1. Calculation of Land Surface Temperature (LST)

I. Conversion of Digital No. (DN) to Spectral Radiance (Lλ): The first step is to convert the DN (Digital No.) values of Thermal Band to spectral radiance (Lλ) which is given by USGS, 2020.

Landsat 8: Using the radiance rescaling factor, Thermal Infra-Red Digital No. of Band 10 can be converted to spectral radiance (Lλ) using the following formula:

$$L\lambda = M_L \times Q_{cal} + A_L - O_i$$

Where:

Lλ = Spectral radiance at the sensor’s aperture in (Watts/ (m² * sr * μm)).

M_L = Radiance multiplicative scaling factor for the Band10 given in metadata file.

A_L = Radiance additive scaling factor for the Band 10 given in metadata file.

Q_{cal} = Quantized and calibrated standard product pixel values (DN)

O_i = Correction value for Band 10 is 0.29

Landsat 7 and 5: The first step of the proposed work is to convert the DN (Digital No.) of Landsat 7 Band 6 and Landsat 5 Band 6 images to spectral radiance (Lλ) which is given by USGS, 2020.

$$L\lambda = (LMAX\lambda - LMIN\lambda) / (QCALMAX - QCALMIN) \times (QCAL - QCALMIN) + LMIN\lambda$$

Where:

Lλ = Spectral radiance at the sensor’s aperture in (Watts/ (m² * sr * μm)).

QCAL = Quantized calibrated pixel value in DN

LMAXλ = Spectral radiance scaled to QCALMAX in (Watts/ (m² * sr * μm)) given in metadata file.

LMINλ = Spectral radiance scaled to QCALMIN in (Watts/ (m² * sr * μm)) given in metadata file.

QCALMAX = Maximum quantized calibrated pixel value (correspond to LMAXλ) in DN= 255.

QCALMIN = Minimum quantized calibrated pixel value (corresponding to LMINλ) in DN= 1.

II. Conversion of Spectral Radiance (Lλ) to Top of Atmospheric (TOA) Brightness Temperature:

The brightness temperature is a measurement of the radiance of the microwave radiation travelling upward from the top of the atmosphere to the satellite, expressed in units of the temperature of an equivalent black body. The spectral radiance (Lλ) of Landsat 8, 7 and 5 extracted from the previous equation is converted to Top of atmosphere (TOA) brightness temperature using the thermal constants provided in the metadata file of the satellite imagery. The following formula which is given by USGS, 2020 is as

follow:

$$BT = (K2/\ln(K1/L\lambda+1)) - 273.15$$

Where:

BT = Top of atmosphere brightness temperature (in Kelvin)

$L\lambda$ = Top of Atmosphere (TOA) spectral radiance (Watts/ $(m^2 \times sr \times \mu m)$)

K1 = K1 Constant 1 given in metadata file.

K2 = K2 Constant 2 given in metadata file.

III. Estimation of Land Surface Emissivity (LSE):

According to Sobrino et al., 2002 and Wang et al., 2015 Land surface emissivity (LSE) is the average emissivity of an element of the surface of the Earth calculated from NDVI values. To estimate emissivity from satellite thermal band data, NDVI threshold method was used by quantifying all land surface types.

Normalized Difference Vegetation Index (NDVI): NDVI is a standardized vegetation index commonly used to determine the spatial extent and health of vegetation in an area. Weng's widely used index that considers a spectral band within near infrared wavelength and the other in red wavelength using the below equation:

In Landsat 8, Band 5 is the Near Infra-red and Band 4 is the Red Band.

In Landsat 7 and Landsat 5, Band 4 is the Near Infra-red and Band 3 is the Red Band.

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

Where:

NDVI= Normalized Difference Vegetation Index.

RED= DN values from the RED band.

NIR= DN values from Near-Infrared band.

NDVI ranges between -1 to +1 where +1 highlights the vegetation and -1 represents all the feature other than vegetation.

In Landsat 8 Emissivity is calculated by: Proportion of Vegetation

According to Meijun et al., 2015 and Quintano et al., 2015, proportion of vegetation (PV) computed by using NDVI values:

$$PV = [(NDVI - NDVI \min) / (NDVI \max + NDVI \min)]^2$$

Where:

PV = Proportion of Vegetation

NDVI = DN values from NDVI Image

NDVI min = Minimum DN values from NDVI Image

NDVI max = Maximum DN values from NDVI Image

$$\varepsilon = 0.004 \times PV + 0.986$$

Where:

ε = Land Surface Emissivity

PV = Proportion of Vegetation

In Landsat 7 and Landsat 5 emissivity is calculated by:

The emissivity can be calculated from NDVI. When NDVI values range from 0.157 to 0.727, Van De Griend and Owe gave an effective equation as follows:

$$\varepsilon = 1.009 + 0.0047 \ln(NDVI)$$

IV. Land Surface Temperature (LST): Avdan and Jovanovska, 2020 they developed the calculation of the Land Surface Temperature (LST) is the radiative temperature which is calculated using Top of Atmosphere

(TOA) Brightness temperature, Wavelength of Emitted radiance, Land Surface Emissivity developed by

$$LST = BT / (1 + (\lambda \times BT / \rho) \times \ln(\varepsilon))$$

Where:

BT = Top of atmosphere brightness temperature ($^{\circ}C$)

λ = Wavelength of emitted radiance which is 10.895.

$\rho = (h \times c) / \sigma$ which is equal to 1.438×10^{-2} mK in which, σ is the Boltzmann constant (1.38×10^{-23} J/K),

h is Plank's constant (6.626×10^{-34}) and c is the velocity of light (3×10^8 m/s).

ε = Land Surface Emissivity

4.3. Urban Heat Island Intensity

Different points that were obtained with the aid of Google Maps were overlaid on the land surface temperature maps using the ArcGIS 10.5 to extract the temperature values for each of the points both rural and urban and thereby calculate UHI using the formula:

$$UHI = Tu - Tr$$

Where:

Tu = LST of the selected urban location on the study area.

Tr = LST of the selected rural location on the study area.

4.4. Calculation Of Normalized Difference Built- Up Index (NDBI)

NDBI is commonly used index to map the built-up areas and barren lands (Estoque et al., 2017; Rousta et al., 2020; Simwanda and Murayama, 2020; Zha et al., 2003). Built-up areas experience a drastic increase in reflectance in the Shortwave Infrared (SWIR) wavelength range (1.55-1.75) μm and are markedly lower in the Near Infrared (NIR) wavelength i.e., (0.76-0.90) μm . The value of NDBI is between -1 and +1, where the negative values indicate water body and positive values represent areas that have higher built-up and other paved surface areas. Whereas zero NDBI values represent areas covered with vegetation. This index can be computed as:

$$NDBI = (SWIR - NIR) / (SWIR + NIR)$$

In Landsat 7 and Landsat 5, Band 5 is the short wave Infra-red and Band 4 is the Near Infra-red Band.

In Landsat 8, Band 6 is the short wave Infra-red and Band 5 is the Near Infra-red Band.

4.5. Zonal Statistics

Zonal statistic function summarizes the values of a raster within the zones of another dataset (either raster or vector) and reports the results as a table. Zonal statistics tables were generated in ARC GIS 10.5 software in order to determine the relationship between Land Use/ Land Cover classes and the difference in land surface temperatures between 2002-2020. The zonal statistics tool provides a summary of simple statistics based on groups. For this analysis, land surface temperatures were summarized by the No. of classes used in this work: Water, Urban Built-Up, Vegetation, Agriculture and Barren Land. Output statistics includes minimum, maximum, mean, standard deviation, range, area, and sum values.

4.6. Regression Analysis

The most commonly used techniques for investigating the relationship between two quantitative variables are correlation and linear regression. Correlation quantifies the

strength of the linear relationship between a pair of variables, whereas regression expresses the relationship in the form of an equation. In this study regression analysis was applied for analysing LST, NDVI and NDBI through extracting points from LST, NDVI and NDBI image pixel values, that is, 50,50 for each study. Linear regression analysis was used and scatter plots were developed. Coefficient of correlation was calculated with the help of

R² values.

5. Results and Discussion

5.1. Spatio-temporal pattern of LULC

Figure No. 3, 4 and 5 show the spatial extent and different patterns of Land Use/ Land Cover (LULC) over the years of 2002, 2010, and 2020 in Lucknow City.

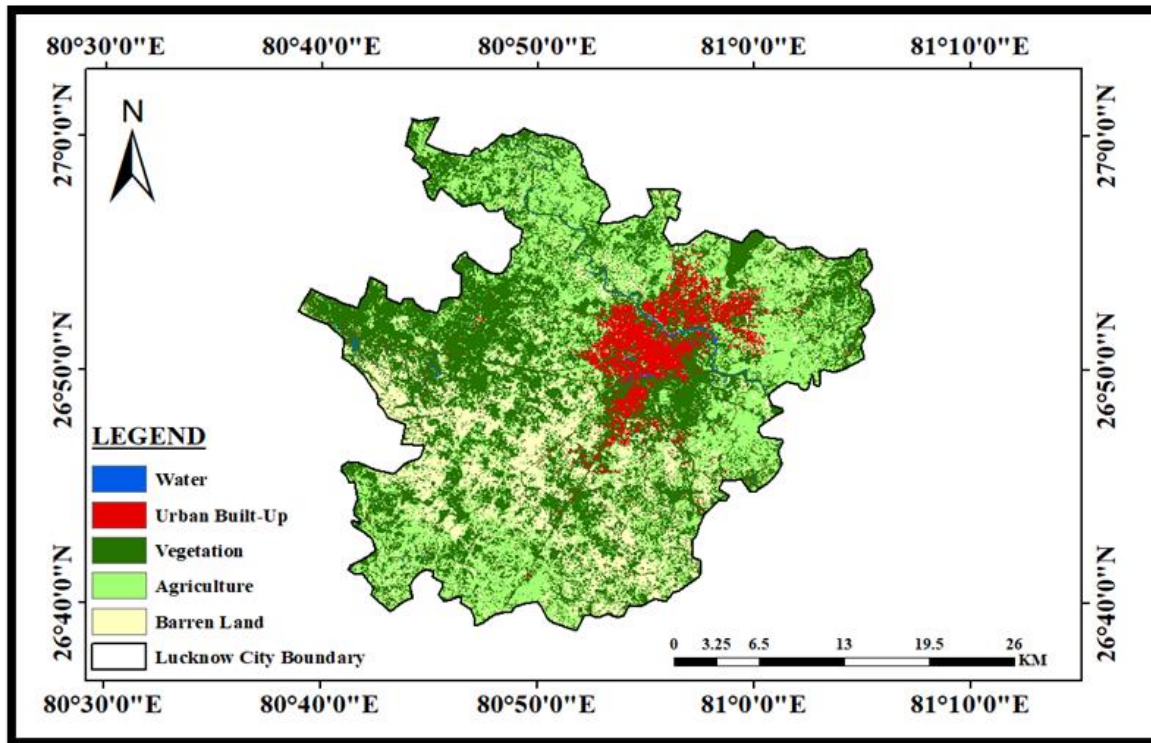


Fig. 3: LULC of Lucknow City (2002)

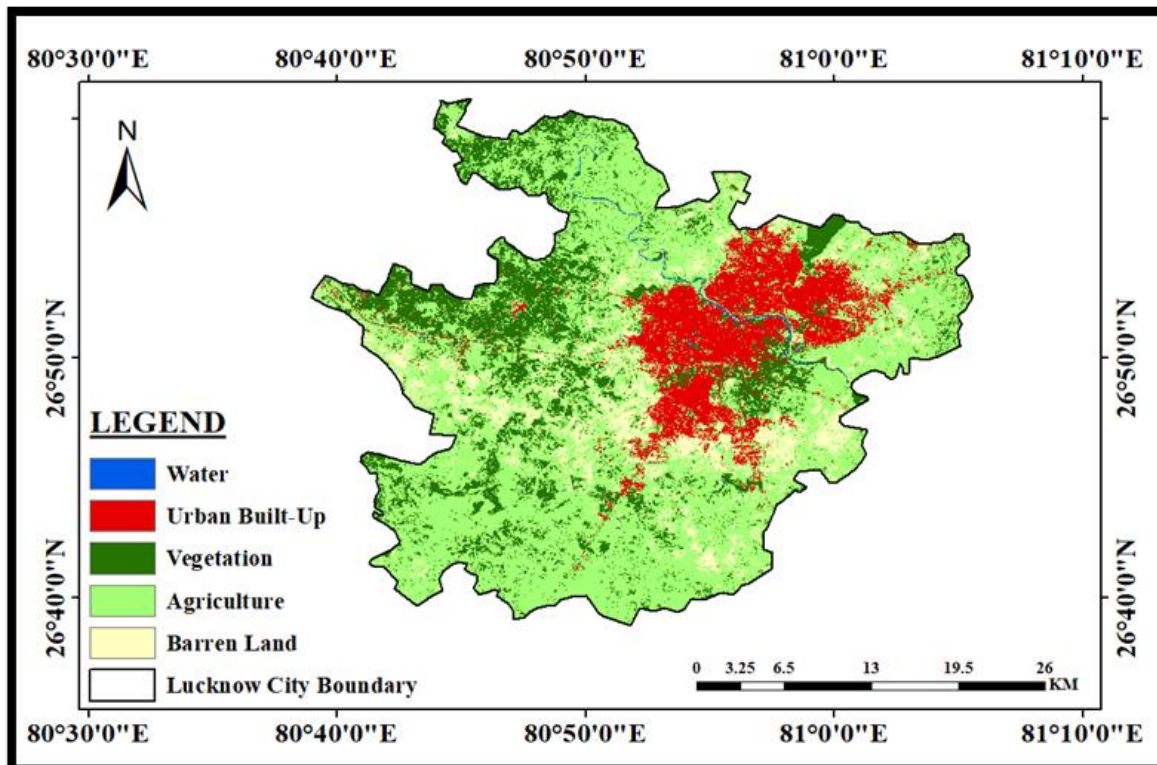


Fig. 4: LULC of Lucknow City (2010)

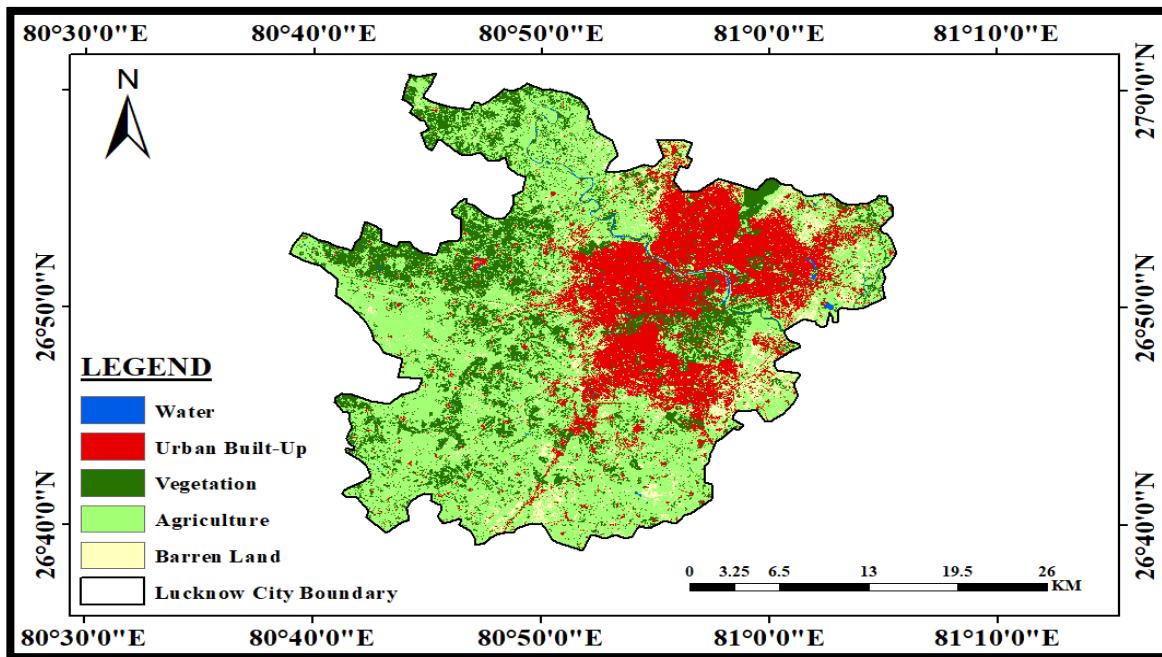


Fig. 5: LULC of Lucknow City (2020)

The temporal pattern between 2002-2020 reflects that urban built-up areas are located centrally on both the left and right sides of the Gomti River. According to all three LULC images, agriculture is the dominant LULC class. Vegetation is majorly found on the western side, and small

patches of vegetation are found around the urban built-up area.

The statistical analysis of LULC in Lucknow City can be seen in Figure No. 6 and 7, and the change detection of LULC in Lucknow City can be seen in Figure No. 8 and 9.

Table 3: Statistical Summary of LULC in Lucknow City (2002-2020)

LULC Types	2002		2010		2020	
	Km ²	%	Km ²	%	Km ²	%
Water	8.12	0.83	7.77	0.79	6.35	0.65
Urban Built-Up	59.75	6.09	126.84	12.95	214.88	21.88
Vegetation	437.85	44.60	176.51	17.98	200.04	20.38
Agriculture	295.46	30.10	568.06	57.86	508.49	51.80
Barren Land	180.52	18.38	102.52	10.42	51.94	5.29
Total	931.7	100	931.7	100	931.7	100

The total area of the study area is estimated to be 981.7 km². In the year 2002, the urban built-up area was denser in the centre of Lucknow City. The urban fringe zone is partially filled with urban built-up and agricultural landforms. In 2002, the urban built up area was 59.75 km², or about 6.09%, which was drastically increased to 126.84 km², or 12.95%, in 2010 due to the increment in population

growth, and 21.88% in 2020, covering an area of 214.88 km². This drastic increase in urban built-up areas was due to the rapid increase in population, also resulting in the construction of residential, commercial, industrial, public utilities, defence areas etc. At the expense of barren land and mostly vegetation, these built-up areas were greatly expanded.

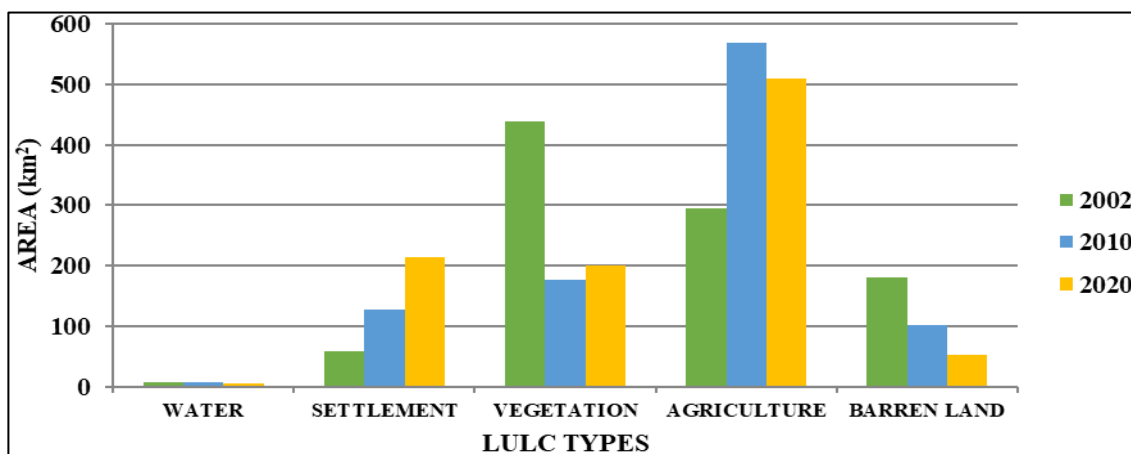


Fig. 6: Statistical analysis showing LULC in Lucknow City (2002-2020) in area km²

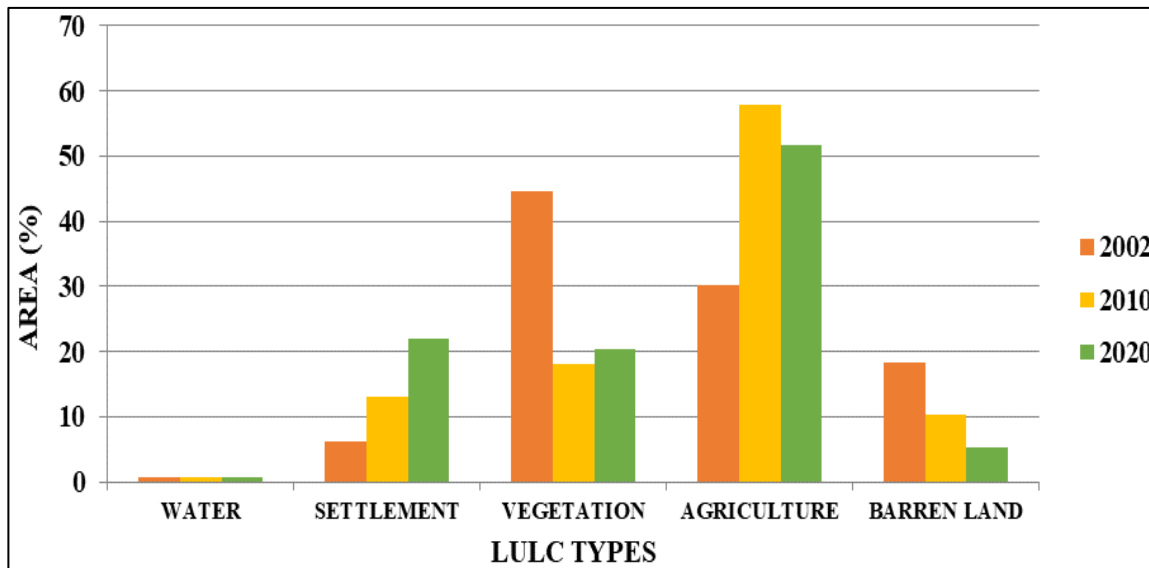


Fig. 7: Statistical analysis showing LULC in Lucknow City (2002-2020) in %

In 2002, vegetation cover in Lucknow City was higher than the national average which was 437.85 km², or about 44.60%, which was later reduced to 17.98%, or about 176.51 km² due to the rapid increase in urban built-up area and population. In 2010, the vegetation LULC class was replaced by agricultural fields, barren land, and urban built up LULC classes. However, in 2020, vegetation cover slightly increased to 20.38%, covering an area of about 200.04 km² because of the expansion of green spaces, tree plantations, recreation areas, etc.

Agriculture, the dominant LULC class, covered 295.48 km² of area in 2002, which was about 30.10% of Lucknow City, which increased to 57.86%, covering an area of about

568.06 km² in 2010 due to an increase in population, resulting in increased agricultural activity as a source of economic income. Due to the rapid increase in built-up areas, agricultural land was slightly reduced in 2020 to 508.49 km². However, the water bodies in 2002 was 0.83%, that is about 8.12 km², which was reduced to 7.77 km² in 2010, and to 0.65%, covering an area of about 6.35 km² in 2020. Hence, the Gomti river can be seen depleting since the last few years. Due to the drastic increase in urban built-up areas, in 2002, barren land was 180.52 km², which was reduced to 102.52 km² in 2010 and to 51.94 km² in 2020.

Table 4: Statistical Summary of LULC change in Lucknow City (2002- 2020).

LULC Types	2002-2010		2010-2020		2002-2020	
	Km ²	%	Km ²	%	Km ²	%
Water	-0.35	-0.04	-1.42	-0.14	-1.77	-0.18
Settlement	67.09	6.86	88.04	9.23	155.13	15.79
Vegetation	-261.34	-26.62	23.53	2.4	-237.81	-24.22
Agriculture	272.6	27.76	-59.57	-6.06	213.03	21.70
Barren Land	-78	-7.96	-50.58	-5.13	-128.58	-13.09



Fig. 8: Statistical analysis showing LULC change in Lucknow City (2002- 2020) in area km²

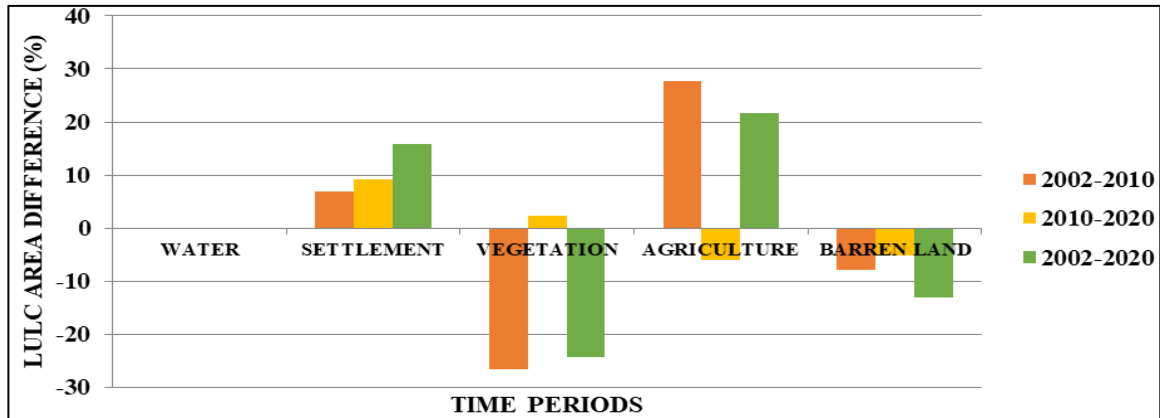


Fig. 9: Statistical analysis showing LULC change in Lucknow City (2002-2020) in %

Thus, this decline in vegetation, agriculture, water bodies, and barren land and the simultaneous increase in urban built-up areas indicates that there was a rapid urbanisation from 2002 to 2020, thus resulting in urban sprawl in Lucknow City.

5.2. Spatial temporal pattern of LST

The spatio-temporal pattern of LST in Lucknow City is illustrated in Figure No. 10, 11, and 12. The statistical information is presented in Table No. 5 and in Figure No. 13.

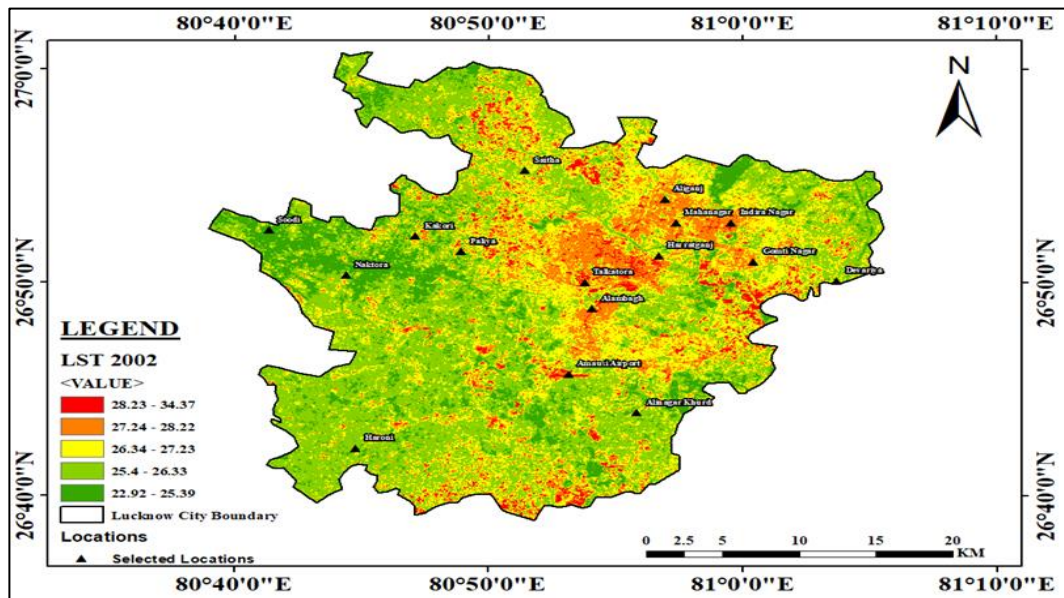


Fig. 10: Land Surface Temperature (LST) of Lucknow City (2002)

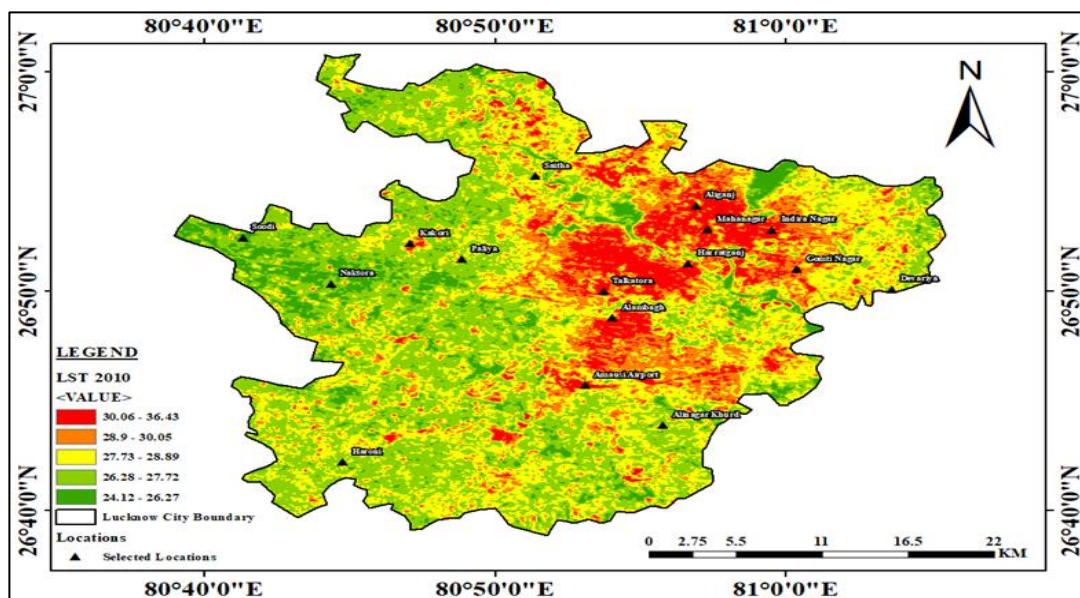


Fig. 11: Land Surface Temperature (LST) of Lucknow City (2010)

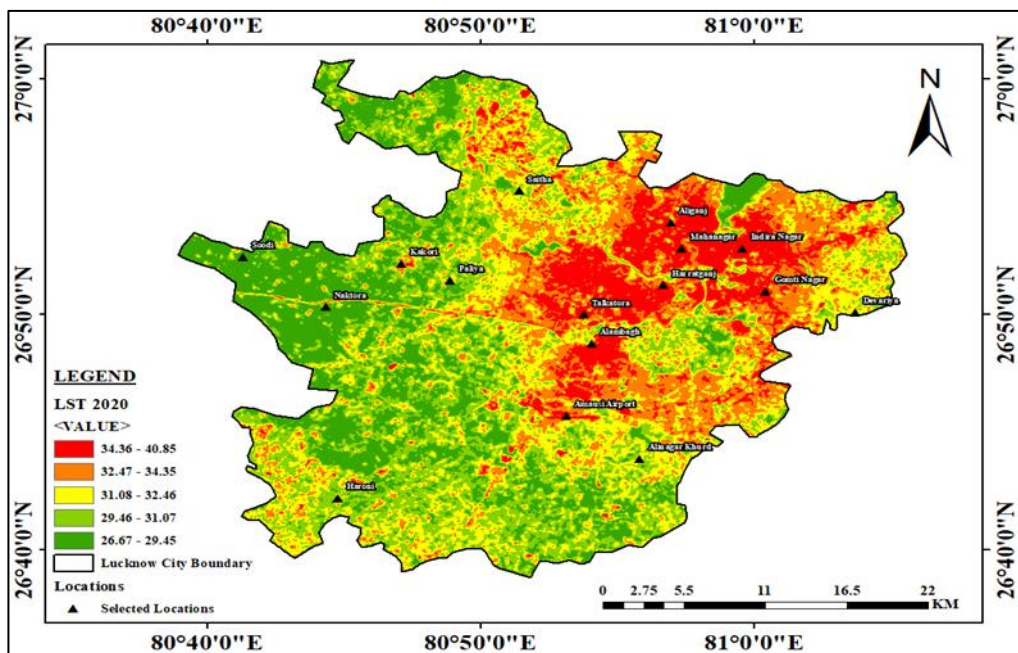


Fig. 12: Land Surface Temperature (LST) of Lucknow City (2020)

The Land Surface Temperature (LST) was calculated for three years, namely 2002, 2010 and 2020. These images were taken during the daytime in the month of September for 2002 and 2010, while the 2020 images were taken in the month of October. During these three selected periods, the LST can be seen increasing in the centre area of Lucknow City, where the main Lucknow City is located. However, lower LST is experienced in the rural areas i.e., the areas on the largely on western side (Naktora, Kakori etc.) and

southern side (Haroni etc.) and some pockets in eastern side (Devariya etc.), in vegetation areas (Kukrail forest, Badi Jugauli Forest, Mussabagh Park, Lohia Park, Janeshwar Mishra Park, dense forest on western side etc.) and on the Gomti river and other waterbodies. Also, the barren lands on the southern side produce high radiance, giving rise to increased LST values. A defined difference between vegetation and urban built-up areas can also be easily seen in the given LST images.

Table 5: Statistical Summary of LST (°C) values in Lucknow City (2002–2020)

Year	Max	Min	Mean	Standard Deviation	Mean LST (°C) Difference		
					2002-2010	2010-2020	2002-2020
2002	34.37	22.92	26.56	1.24	-1.61	-3.2	-4.77
2010	36.45	24.12	28.13	1.28			
2020	40.85	26.67	31.33	1.81			

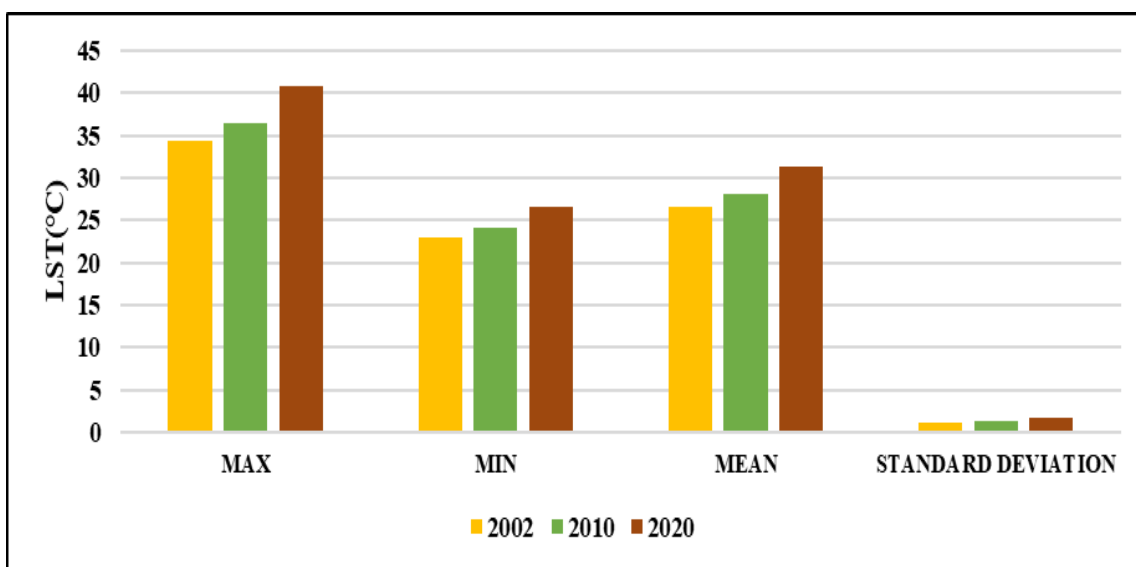


Fig. 13: Statistical Summary of LST (°C) values in Lucknow City (2002–2020)

On 30th September, 2002 Lucknow City had a minimum and maximum LST of 22.92°C and 34.37°C, the intensity of LST is less in 2002. In Figure No. 10, we can see that

the range of hot spots is very minimal compared to other years. It was observed in 2002 that the surface temperatures of the core areas of Lucknow City (Gomti Nagar 30.84°C,

Hazratganj 30.52°C, Indira Nagar 30.43°C, Amausi 31.25°C etc.) were the highest which ranges approximately between 29°C-32°C. Areas surrounding the built-up and some other open places or bare ground (Devariya 28.94°C, Alinagar Khurd 27.94°C, Paliya 27.52°C, Saitha 28.19°C etc.) in the study area experienced the temperature values ranging from 27°C – 30°C while the larger part of the area had surface temperature values ranging between 22.92°C – 26.33°C. It could be said that Lucknow City is in the initial stage of the Urban Heat Island (UHI) phenomenon.

In Figure No. 11, we can see the increasing effect of urban heat island (UHI) as the LST has increased in the central portion of Lucknow City in comparison to 2002. On September 28th, 2010, Lucknow City had a minimum and maximum LST of 24.12°C and 36.45°C. The LST of urban built-up area in the centre has increased in comparison to 2002. The LST of 2010 is 1.61°C higher than the LST of 2002. The LST of the urban areas i.e., Hazratganj 33.28°C, Gomti Nagar 32.08°C, Alambagh 32.67°C etc. ranges approximately between 30°C and 34°C and that of the rural areas i.e., Saitha 28.75°C, Devariya 28.83°C, Paliya 28.34°C, Naktora 28.83°C etc. ranges between 28°C and 30°C.

In 2020, on October 9th, Lucknow City had a minimum LST of 26.67°C and a maximum LST of 40.85°C. Because of increased built-up areas, the LST in 2020 increased by 3.2°C compared to the LST in 2010. The LST in urban areas i.e., Gomti nagar 34.08°C, Amausi 34.36°C, Alambagh 34.93°C, Indira Nagar 34.03°C etc. is between 32°C and 35°C, while in rural areas i.e., Saitha 28.53°C, Paliya 29.67°C, Naktora 29.16°C etc. it is between 28°C and 30°C. Thus, an increasing UHI effect can be seen over Lucknow City.

Compared to the images of all three years, it can be noted that the year 2010 has a significantly higher UHI effect than 2002 and has many new emerging hot spots such as Gomti nagar, Hazratganj, Indira Nagar, Talkatora, Alambagh. In 2020, the UHI effect is very well visible as the urban land expands. Thus, the UHI phenomenon can be clearly seen in Lucknow City especially in the areas of Gomti nagar, Hazratganj, Indira Nagar, Talkatora, Alambagh.

Comparing LST and LULC

By comparing the results of the Land Use/ Land Cover (LULC) of Figure No. 3, 4 and 5 with the land surface temperature results of Figure No. 10, 11, and 12, it was

observed that the high temperature was associated with built-up areas such as Gomti nagar, Hazratganj, Indira Nagar and areas of anthropogenic activities like industrial region such as Talkatora (Eveready Industries (India) Ltd.), Amausi (Amar Ujala Publication Ltd., Shyam Vanaspati Ltd.), Alambagh (PTC Industries) etc.

The lowest temperature corresponds to areas that are densely vegetated and also consist of water bodies. These results confirmed that surface temperature will always be lower over the vegetation compared to bare or exposed soil because the canopy intercepts the incoming short-wave solar radiation. It reflects little and absorbs a large amount, which is converted to chemical energy that aids photosynthesis with the help of chlorophyll and loses excess energy to the process of evapotranspiration. An open or bare surface cannot intercept incoming short radiation therefore it absorbs more energy and emits more to the surroundings in the form of long terrestrial waves resulting a rise in the temperature of the near surface air. Building materials used nowadays have varying capacities for physical surface properties like albedo, thermal capacity, and heat conductivity that act as a major contributing factor to the environmental thermal increase.

5.3. Spatial analysis of Land surface temperature (LST) by Land Use/ Land Cover (LULC) class

Zonal statistics for 2002 indicate that Land Surface Temperatures associated with barren land located in the southern direction of the study area has the surface pixels of an average temperature of 27.99°C, with the built-up resulting in the highest average temperature of 30.16°C (standard deviation of 1.03) located in a radial pattern in the centre of the study area i.e., Hazratganj, Gomti Nagar, Indira Nagar, Mahanagar etc. The lowest average surface temperature was observed for the water class i.e., Gomti river at 27.46°C. In 2010, the highest surface temperature was associated with a built-up area, at 31.38°C and the standard deviation was 1.17. The barren land surface increased to 28.37°C. In 2020, the highest average temperature, however, was associated with the built-up class at 34.08°C. The lowest surface temperatures correspond to the water class at 29.60°C. Hence, the land use and land cover exhibited the largest change in temperature between 2002 to 2020 in the urban built-up area visible in the pockets of Hazratganj, Gomti Nagar, Alambagh, Mahanagar, Talkatora, Aliganj, Amausi, Indira Nagar.

Table 6: Statistical Summary of Land Surface Temperature (LST) by Land Use/ Land Cover (LULC) class of Lucknow City (2002–2020)

Year	2002 Average Temperature(°C)		2010 Average Temperature(°C)		2020 Average Temperature(°C)	
	MEAN	STD	MEAN	STD	MEAN	STD
Water	27.46	1.31	28.68	1.12	29.60	1.37
Urban Built-Up	30.16	1.03	31.38	1.17	34.08	1.36
Vegetation	27.85	1.19	28.74	1.11	30.18	1.58
Agriculture	28.30	1.08	29.87	1.44	30.37	1.95
Barren Land	27.99	1.21	28.37	1.47	31.38	1.55

5.4. Urban Heat Islands Intensity

5.4.1. Urban Rural Temperature differences

Urban centres tend to have higher air temperatures than rural areas in its vicinity as a result of vegetation cover being replaced by non-porous, non-evaporating, highly thermally conductive surfaces such as concrete and asphalt.

The UHI is commonly described by UHI Intensity (Tu-Tr), which is measured as the difference in air temperature between an urban area (u) and its rural surroundings (r). Table No. 7, 8, and 9 displays various urban and rural sample locations in 2002, 2010, and 2020, respectively.

Table 7: Mean Temperature and UHI for 2002

Urban Location	Urban Temp. (Tu)	Rural Location	Rural Temp. (Tr)	UHI(Tu-Tr) in (°C)
Amausi	31.25	Devariya	28.94	2.31
Talkatora	29.61	Soodi	28.26	1.35
Gomti Nagar	30.84	Naktora	27.68	3.16
Indira Nagar	30.43	Kakori	29.18	1.25
Alambagh	30.84	Alinagar Khurd	27.94	2.9
Hazratganj	30.52	Saitha	28.19	2.33
Mahanagar	30.02	Paliya	27.52	2.5
Aliganj	30.43	Haroni	27.41	2.91

The highest LST of 31.25°C is associated with urban areas and the lowest, at 27.41°C, in the suburban areas in 2002. In 2002, the highest was found in the urban and the lowest

in the suburban, at 33.28°C and 28.17°C, respectively. 2020 was no exception, as the highest was found to be 34.93°C and the lowest in the suburbs to be 27.74°C.

Table 8: Mean Temperature and UHI for 2010.

Urban Location	Urban Temp. (Tu)	Rural Location	Rural Temp. (Tr)	UHI(Tu-Tr) in (°C)
Amausi	31.24	Devariya	28.83	2.41
Talkatora	32.67	Soodi	29.87	2.8
Gomti Nagar	32.08	Naktora	28.83	3.25
Indira Nagar	32.19	Kakori	30.76	1.43
Alambagh	32.67	Alinagar Khurd	29.34	3.33
Hazratganj	33.28	Saitha	28.75	4.53
Mahanagar	31.72	Paliya	28.34	3.38
Aliganj	32.19	Haroni	28.17	4.02

Table 9: Mean Temperature and UHI for 2020.

Urban Location	Urban Temp. (Tu)	Rural Location	Rural Temp. (Tr)	UHI(Tu-Tr) in (°C)
Amausi	34.36	Devariya	29.63	4.73
Talkatora	34.74	Soodi	27.74	7
Gomti Nagar	34.08	Naktora	29.16	4.92
Indira Nagar	34.03	Kakori	32.1	1.93
Alambagh	34.93	Alinagar Khurd	30.65	4.28
Hazratganj	33.47	Saitha	28.53	4.94
Mahanagar	33.96	Paliya	29.67	4.29
Aliganj	33.12	Haroni	29.01	4.11

Figure No.14 revealed the intensity at different locations over Lucknow City. For all the locations considered, there was a wide variation of UHI intensity from 2002 to 2020. In 2002, the maximum was recorded to be 3.16°C (between Gomti Nagar located in the east from Lucknow city centre and Naktora located in the western side away from the Lucknow city) and the lowest was 1.25°C (between Indira Nagar located in northern direction and Kakori located in the west). The UHI intensity was found to be maximum 4.53°C (between Hazratganj which is the central part of the city and Saitha located in the north-western side) and the minimum was 1.43°C (between Indira Nagar and Kakori)

in 2010. There was a tremendous increase in intensity in 2020 across the locations. The maximum intensity was observed to be 7°C (between Talkatora located in Cis Gomti region and Soodi located in the extreme west side of the study area) while the minimum intensity was 1.93°C (between Indira Nagar and Kakori). The intensity of Urban Heat Island over Lucknow City has been increasing continuously over the years as revealed in this study. The average increase for 2002, 2010 and 2020 were observed to be 2.34°C, 3.14°C and 4.56°C respectively.

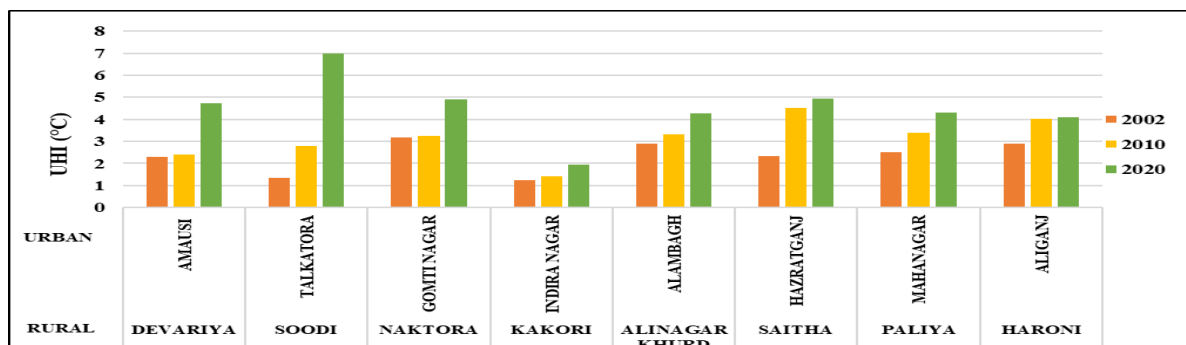


Fig 14: Urban intensity at different locations over Lucknow City (2002- 2020).

5.5. Spatial temporal pattern of NDVI and its relationship with LST

The spatio-temporal pattern of NDVI in Lucknow City is illustrated in Figure No. 15,16 and 17.

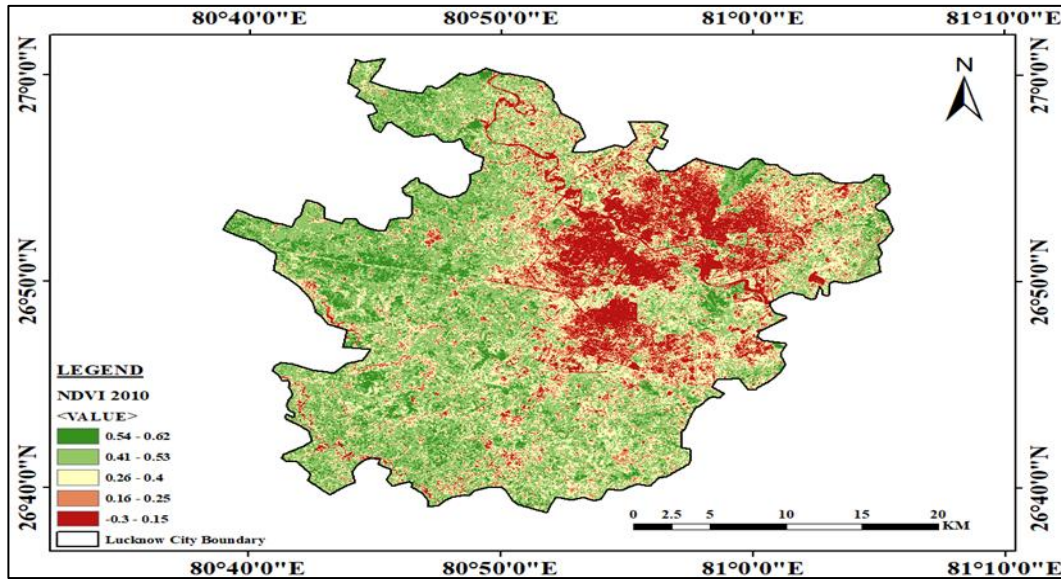


Fig. 15: Normalized Difference Vegetation Index (NDVI) of Lucknow City (2002)

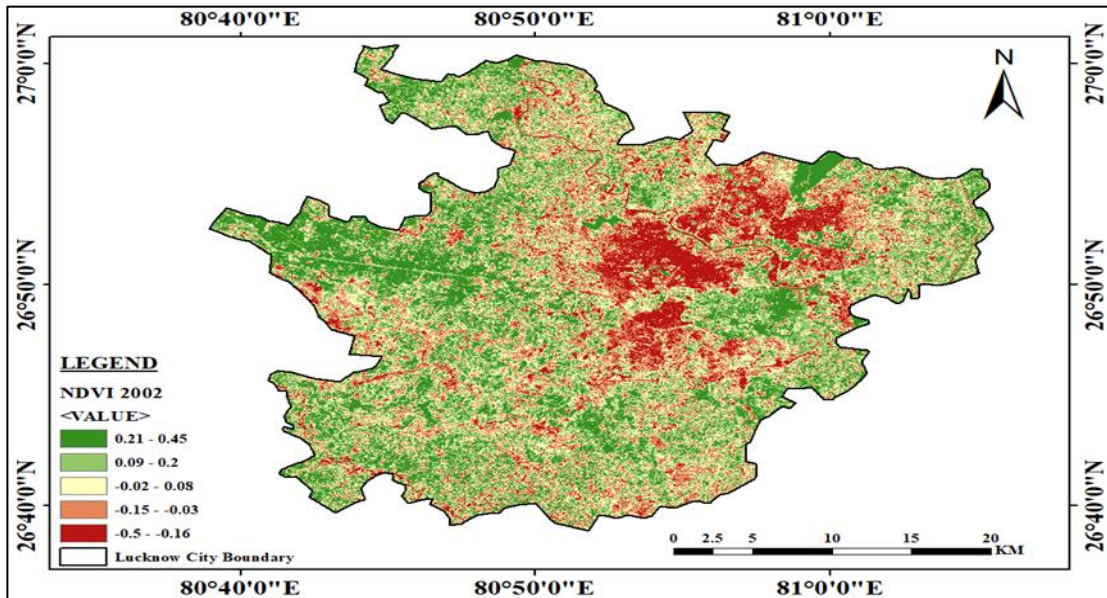


Fig.16: Normalized Difference Vegetation Index (NDVI) of Lucknow City (2010)

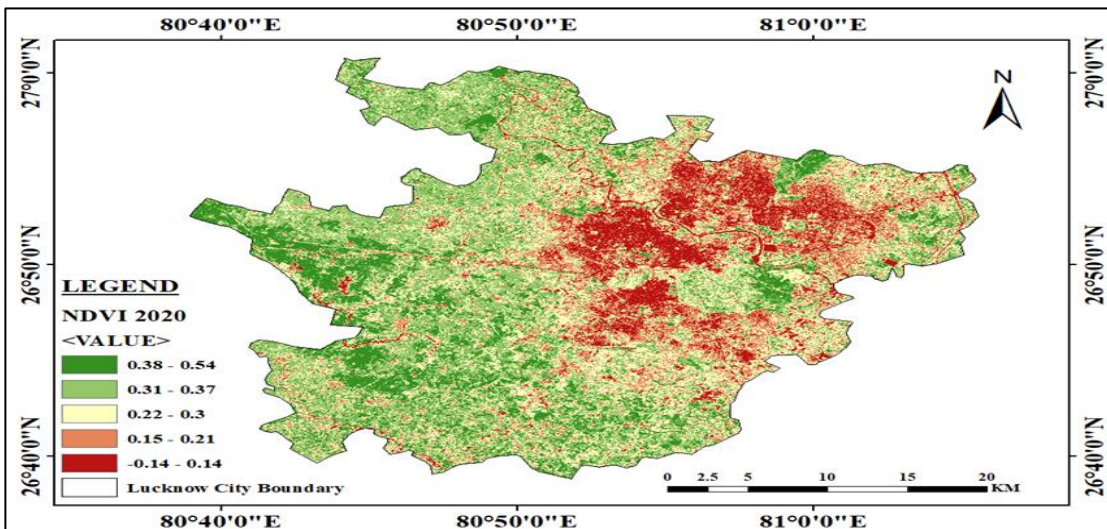


Fig. 17: Normalized Difference Vegetation Index (NDVI) of Lucknow City (2020)

The NDVI value revealed that lower NDVI is associated with the developed settlements while high NDVI values is associated with the less developed natural surfaces. The statistical information is presented in Table No. 10 and Figure No. 18. Areas having high vegetation such as

Kukrail forest, dense forest on western side, Badi Jugauli Forest, Mussabagh Park, Lohia Park, Janeshwar Mishra Park has high NDVI values. LST builds an inverse relationship with vegetation.

Table 10: Statistical Summary of NDVI values in Lucknow City (2002–2020)

Year	Max	Min	Mean	Standard Deviation
2002	0.45	-0.5	0.05	0.16
2010	0.66	-0.3	0.35	0.16
2020	0.54	-0.14	0.28	0.09

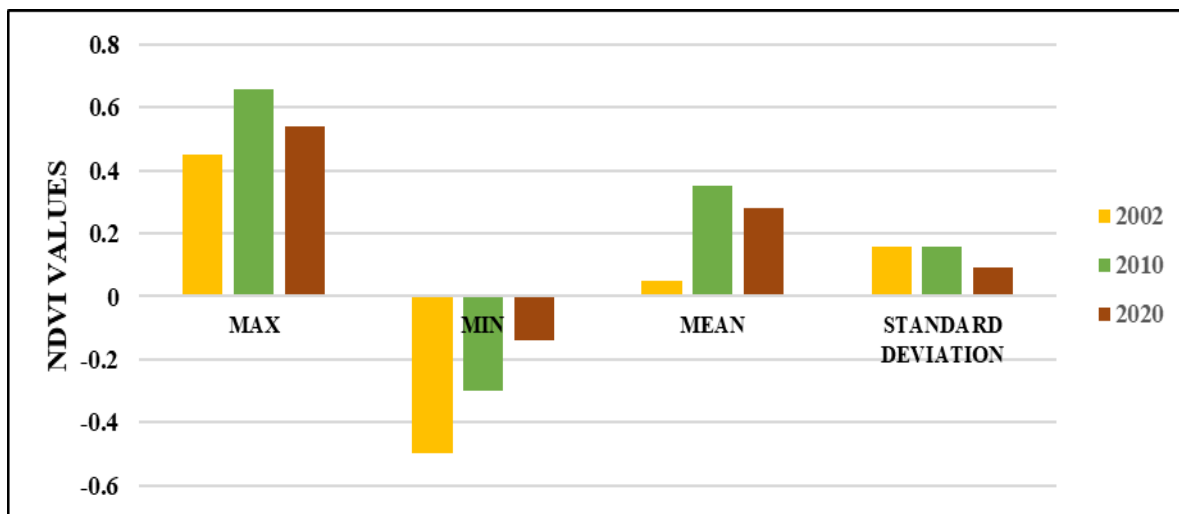


Fig. 18: Statistical analysis of NDVI values in Lucknow City (2002–2020)

In 2002, the maximum value of NDVI is 0.45 and the minimum value of NDVI is -0.5. However, in 2010 maximum and minimum value of NDVI is 0.66 and -0.3. In 2020, the maximum value is 0.54 and the minimum is -0.14.

It is found that NDVI has a negative correlation with LST

as explained in Figure No. 19,20 and 21 which means the increase in vegetation cover in any geographical location will reduce the intensity of the land surface temperature and this could be used as measure to reduce the effect of Urban Heat Island. The correlations coefficient for each year is summarized in Table No. 11 below:

Table 11: Statistical Summary of NDVI values in Lucknow City (2002–2020).

Year	Coefficient of determinant (R^2)	Coefficient of correlation (R)
2002	-0.2759	-0.525
2010	-0.3074	-0.554
2020	-0.219	-0.468

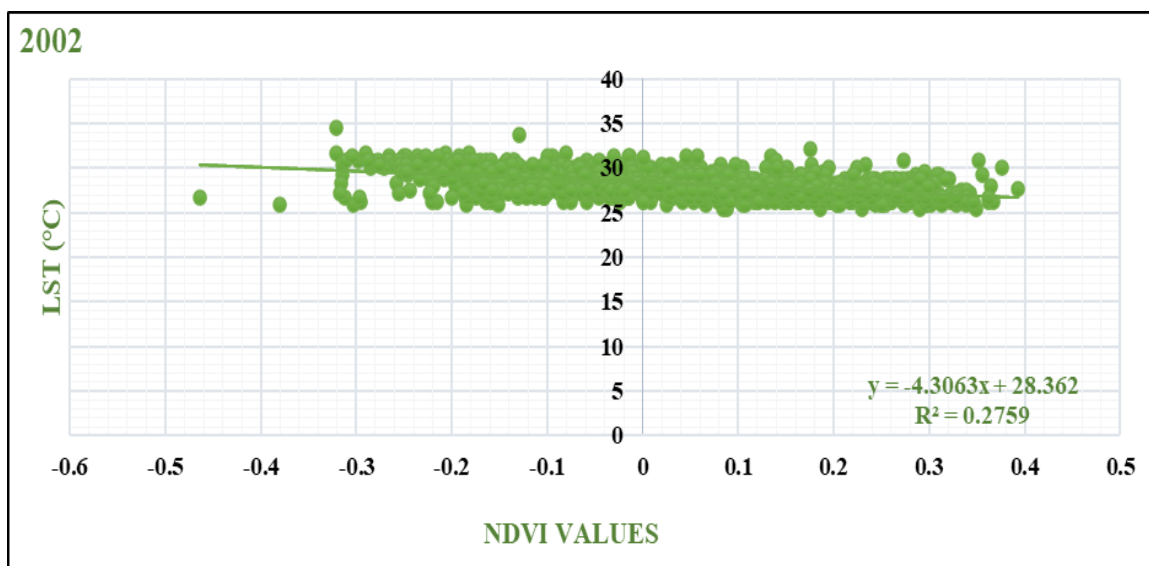


Fig. 19: Scattered plots between LST and NDVI of Lucknow City (2002)

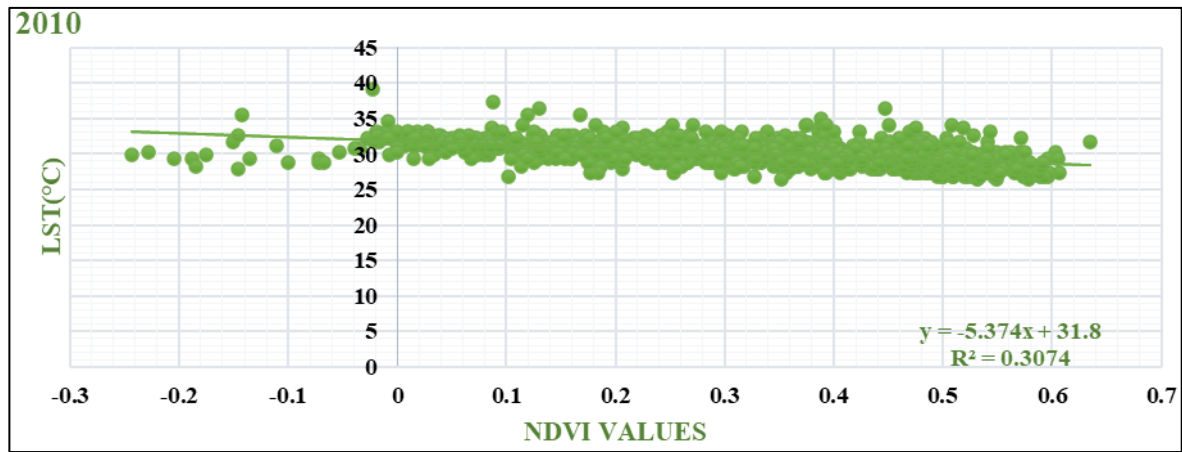


Fig. 20: Scattered plots between LST and NDVI of Lucknow City (2010)

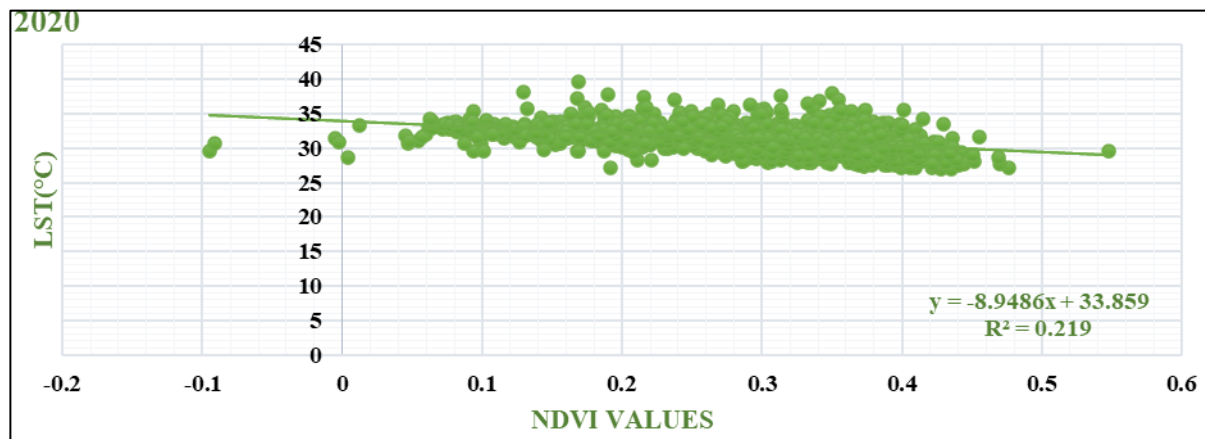


Fig. 21: Scattered plots between LST and NDVI of Lucknow City (2020).

This means that higher the NDVI the lower will be LST and higher the LST the lower will be NDVI. The statistical analysis scatter plots show the negative relationship that exists between LST and NDVI represented by Coefficient of determinant (R^2) and it was -0.2759 in 2002 and -0.3074 in 2010 and then to -0.219 in 2020 and the coefficient of correlation (R) is -0.525 in 2002, -0.554 in 2010 and -0.468 in 2020.

5.6. Spatio temporal pattern of NDBI and its relationship with LST

The spatio-temporal pattern of NDBI in Lucknow City is illustrated in Figure No. 22,23 and 24. The statistical information is presented in Table No. 12 and statistical analysis in Figure No. 25. LST builds a direct relationship with Built-Up area. In 2002, urban built -up area was not much expanded when we compare it with 2010 and 2020. The spatial extent of NDBI increased from the centre to outward direction in a radial pattern because industrial, commercial, residential, defence zone and other public utilities are expanded.

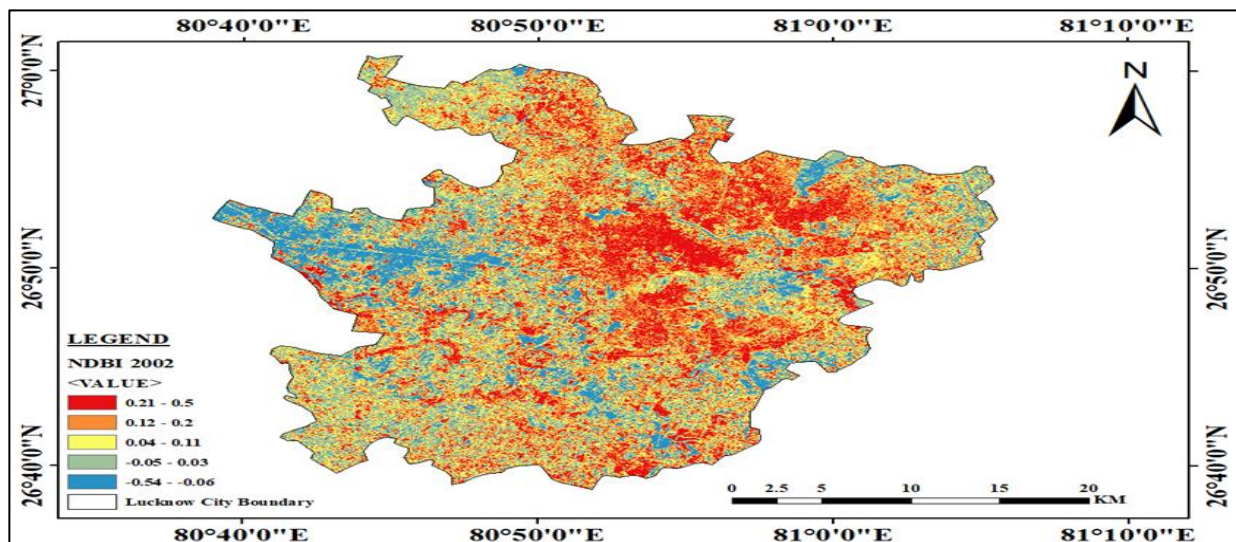


Fig. 22: Normalized Difference Built-Up Index (NDBI) of Lucknow City (2002).

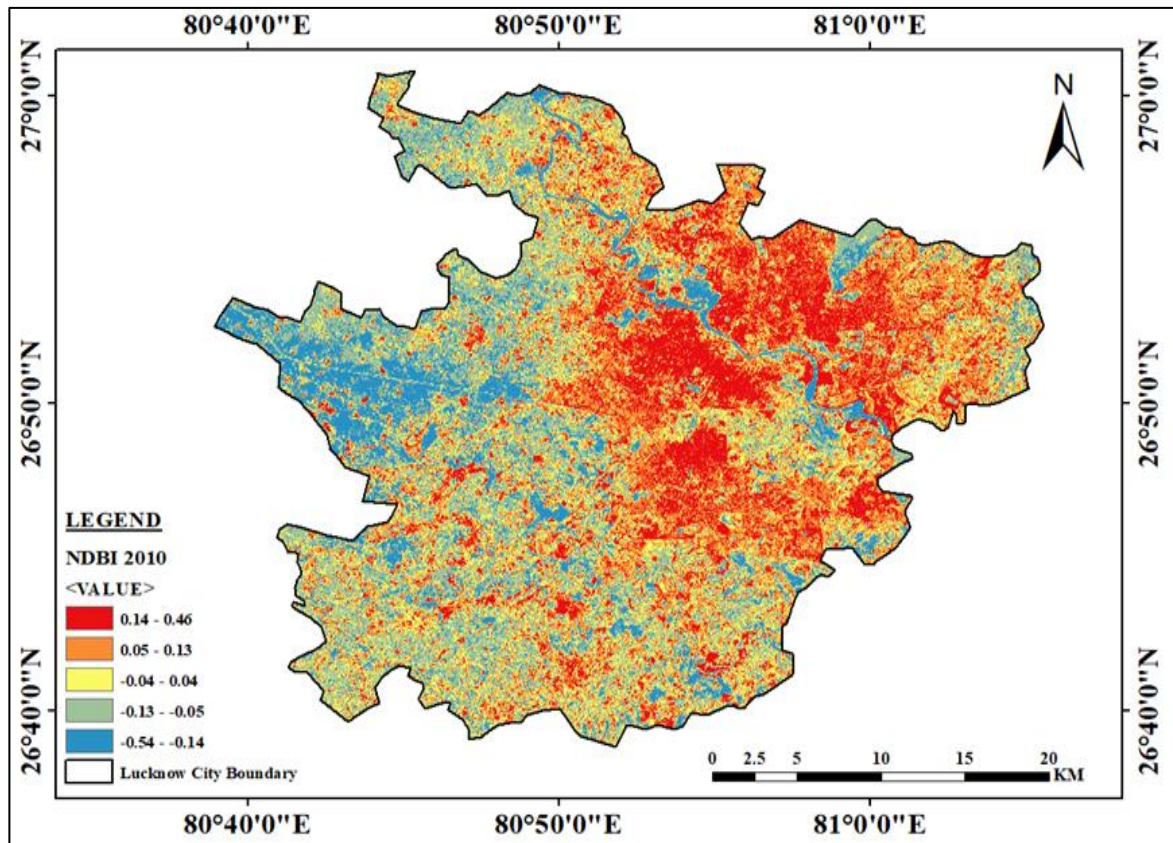


Fig. 23: Normalized Difference Built-Up Index (NDBI) of Lucknow City (2010).

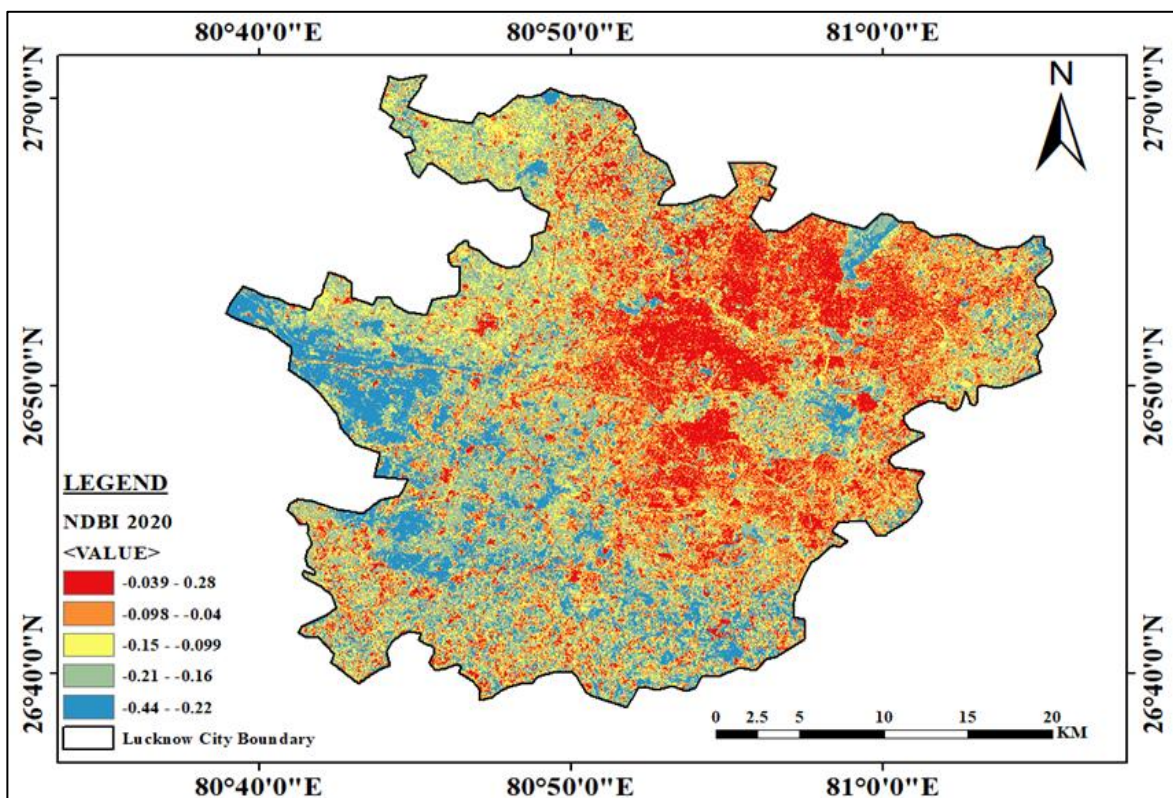


Fig. 24: Normalized Difference Built-Up Index (NDBI) of Lucknow City (2020).

Table 12: Statistical Summary of NDBI values in Lucknow City (2002–2020).

Year	Max	Min	Mean	STD
2002	0.5	-0.54	0.09	0.11
2010	0.46	-0.54	0.01	0.12
2020	0.28	-0.44	-0.13	0.082

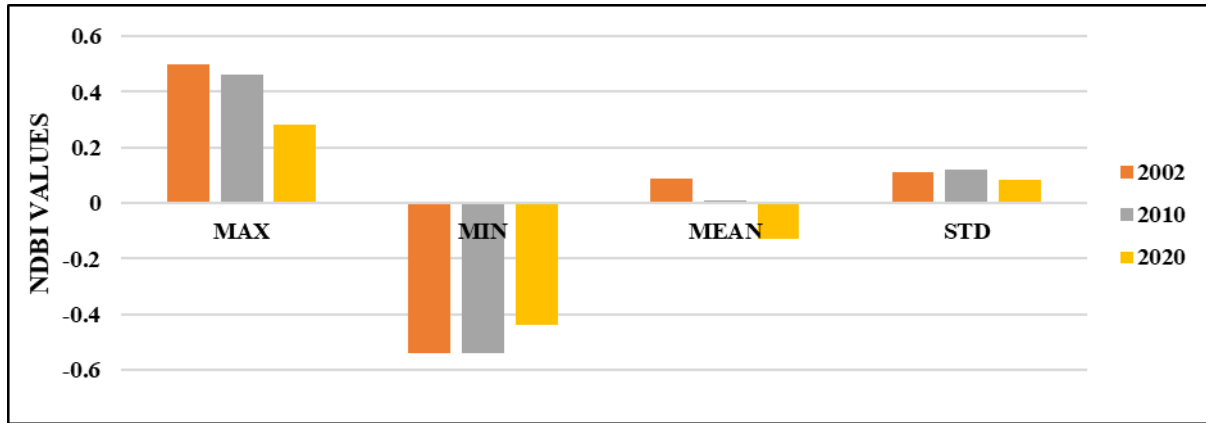


Fig. 25: Statistical analysis of NDBI values in Lucknow City (2002–2020).

In 2002, the maximum value of NDBI is 0.5 and the minimum value of NDBI is -0.54. However, in 2010 maximum and minimum value of NDBI is 0.46 and -0.54. In 2020, the maximum value is 0.28 and the minimum is -0.44.

Therefore, NDBI has a positive correlation with LST, that is the lower in NDBI, the lower in LST and higher NDBI indicate the higher LST. Figure No. 26,27 and 28 shows

that there was a positive relationship between NDBI and LST.

The statistical analysis scatter plots as shown in Table No. 13 shows the negative relationship that exists between LST and NDBI represented by Coefficient of determinant (R^2) and it was 0.2843 in 2002 and 0.3563 in 2010 and then to 0.3673 in 2020 and the coefficient of correlation (R) is 0.533 in 2002, 0.570 in 2010 and 0.606 in 2020.

Table 13: Statistical Summary of NDBI values in Lucknow City (2002–2020).

Year	Coefficient of determinant (R^2)	Coefficient of correlation (R)
2002	0.2843	0.533
2010	0.3563	0.570
2020	0.3673	0.606

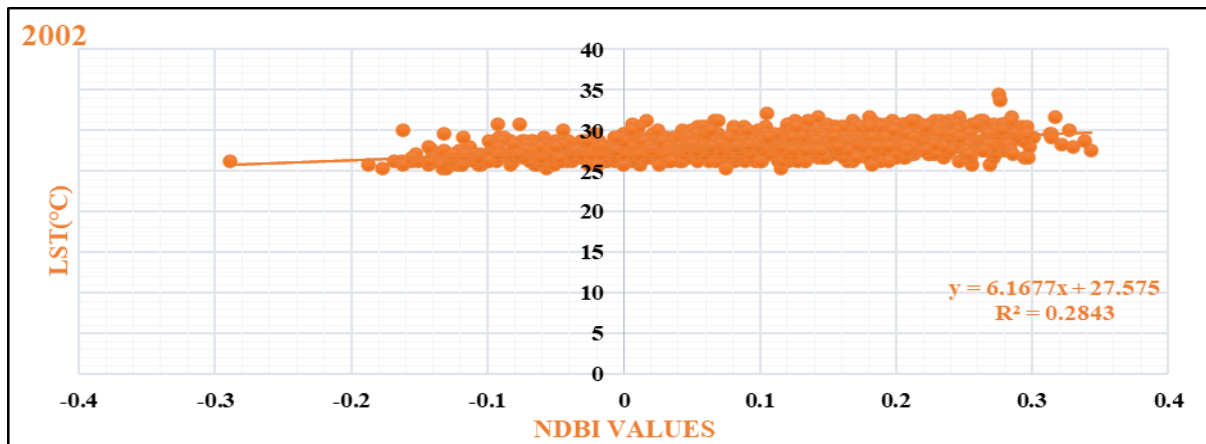


Fig. 26: Scattered plots between LST and NDBI of Lucknow City (2002).

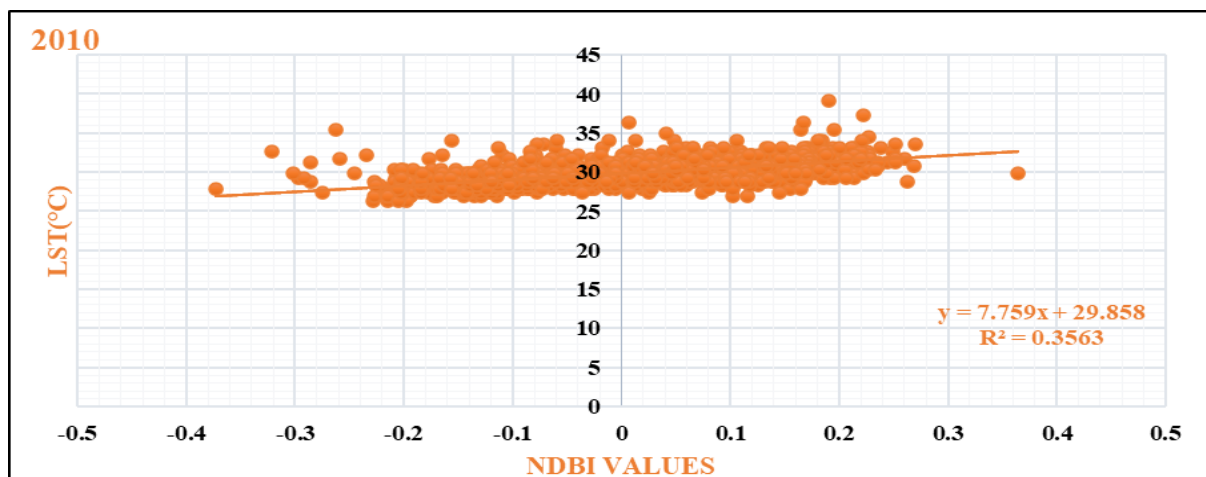


Fig. 27: Scattered plots between LST and NDBI of Lucknow City (2010).

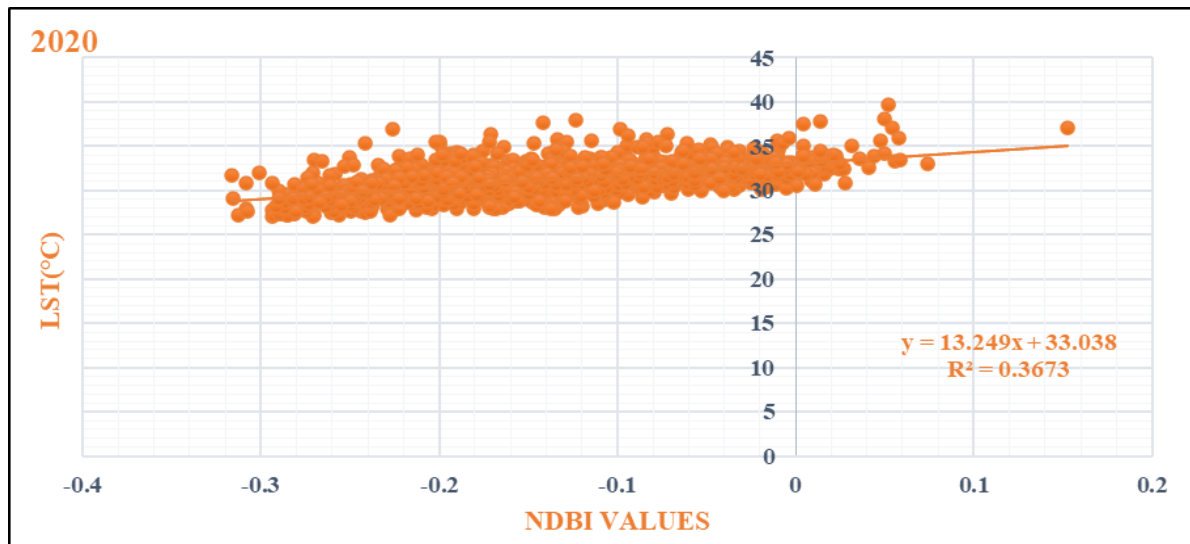


Fig. 28: Scattered plots between LST and NDBI of Lucknow City (2020).

6. Suggestions

Following are the few suggestions which can be incorporated in the future Lucknow's Master Plan when prepared in order to mitigate the rising UHI.

- Strict monitoring by the local administration will restrict the encroachment of the land-use under green-belts as proposed in subsequent Master Plan.
- Unlike most Indian cities, the study area is blessed with the Gomti River which meanders across the city and divides it into two half. Urban forestry along the 12-kilometres of right and left banks of the river will help to control heating-up of the study area and regulate the local weather parameters.
- Social forestry can be incorporated on the vacant land as well on multi-storey parking in Hazratganj, Lalbagh, Aminabad.
- Roof top greenery should be made mandatory by the Lucknow development authority so that different land-use category within the study area will enhance vegetation cover which subsequently will help to reduce negative correlation between Land Surface Temperature (31.33°C) and Normalised Difference Vegetation Index (0.28).
- Urban landscape planning and urban renewal, both in old city areas (such as Chowk, Aminabad, Aishbagh etc.) and newly expansion of built-up areas (such as Gomti Extension, Sushant Golf Green City as well as upcoming new cities developed by Private developers), green spaces including city parks, greenways, green roofs, green buildings and other types of green corridors will create a healthy and viable ambience to the citizens.

These above suggestions will also help in controlling the adverse effect of present climate change and will also help to build an integrated ecological network in urban areas, making the study area more sustainable in the future.

7. Conclusion

The present study analysed the spatio-temporal pattern of different Land Use/ Land Cover (LULC) types and land surface temperatures (LST) of Lucknow City over the last 18 years (2002–2020) with the aid of multi-temporal satellite data to achieve the study's objective i.e., to assess the Urban Heat Island in Lucknow City.

The LULC change analysis shows that the urban built-up area has increased 15.79% i.e., 155.13km² from 2002 to 2020 and vegetation has decreased 24.22% i.e., 237.81km² from 2002 to 2020. Thus, urban sprawl can be detected which is one of the factors responsible for urban heat island. The LST analysis result revealed that the mean LST also increased 4.77°C from 2002–2020. Also, the LST of urban built-up areas is higher in comparison to other LULC classes. The most significant change in mean LST was observed in built-up areas with 3.92°C increase between 2002 to 2020. Similarly, the mean LST of vegetation, barren land, agriculture and water increased by 2.33°C, 3.39°C, 2.07 °C and 2.14°C, respectively. Therefore, the result indicates a substantial LST increase in all the LULC classes. The study further revealed a negative relationship between LST and NDVI while establishing a positive relationship between LST and NDBI during the different periods. This implies that higher LST is experienced along with a decline in vegetation and an increase in built-up areas. Also, the UHI intensity from remotely sensed data shows an average of 4.56°C warmer than the rural areas in the last decade.

The results of the study clearly showed that urbanization in Lucknow City have substantially influenced the city's increase in LST, therefore contributing to the development of surface UHI. Therefore, further research is needed to investigate the city's future LULC changes dynamics and its potential LST variations using various geospatial-modelling techniques. However, the role and importance of vegetation in cities need much more attention in order to efficiently mitigate the UHI effect.

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