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Article

Analysis of Urban Heat Island (UHI) in Relation to Normalized Difference Vegetation Index (NDVI): A Comparative Study of Delhi and Mumbai

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Abstract: The formation and occurrence of urban heat island (UHI) is a result of rapid urbanization and associated concretization. Due to intensification of heat combined with high pollution levels, urban areas expose humans to unexpected health risks. In this context, the study aims at comparing the UHI in the two largest metropolitan cities of India, *i.e.*, Delhi and Mumbai. The presence of surface UHI is analyzed using the Landsat 5 TM image of 5 May 2010 for Delhi and the 17 April 2010 image for Mumbai. The validation of the heat island is done in relation to the Normalized Difference Vegetation Index (NDVI) patterns. The study reveals that built-up and fallow lands record high temperatures, whereas the vegetated areas and water bodies exhibit lower temperatures. Delhi, an inland city, possesses mixed land use and the presence of substantial tree cover along roads; the Delhi Ridge forests and River Yamuna cutting across the city have a high influence in moderating the surface temperatures. The temperature reaches a maximum of 35 °C in West Delhi and a minimum of 24 °C in the east at the River Yamuna. Maximum temperature in East Delhi goes to 30 °C, except the border areas. North, Central and south Delhi have low temperatures (28 °C–31 °C), but the peripheral areas have high temperatures (36 °C–37 °C). The UHI is not very prominent in the case of Delhi. This is proven by the correlations of surface temperature with NDVI. South Delhi, New Delhi and areas close to River Yamuna have high NDVI and, therefore, record low temperatures. Mumbai, on the other hand, is a coastal city with lower tree cover than Delhi. The Borivilli National Park (BNP) is in the midst of dense horizontal and vertical growth of buildings. The UHI is much stronger where the heat is trapped that is, the built-up zones. There are four small rivers in Mumbai, which have low carrying capacity. In Mumbai suburban district, the areas adjoining the creeks, sea and the lakes act as heat sinks. The coastal areas in South Mumbai record temperatures of 28 °C–31 °C; the Bandra-Kurla Complex has a high range of temperature *i.e.*, 31 °C–36 °C. The temperature witnessed at Chattrapati Shivaji International Airport is as high as 38 °C. The temperature is nearly 37 °C–38 °C in the Dorai region in the Mumbai suburban district. The BNP has varied vegetation density, and therefore, the temperature ranges from 27 °C–31 °C. Powai Lake, Tulsi Lake and other water bodies record the lowest temperatures (24 °C–26 °C). There exists a strong negative correlation between NDVI and UHI of Mumbai, owing to less coverage of green and vegetation areas.

Keywords: land surface temperature; land use/cover; urban microclimates; Landsat satellite images; Delhi; Mumbai; metropolitan

1. Introduction

Urban areas, due to intense built-up areas, concrete zones and high concentrations of anthropogenic activities, have led to the development of urban microclimates (UMCs). The development of UMCs is associated with the urban heat island (UHI) phenomenon. Extensive urbanization transforms the land use/cover (LULC), thereby modifying the energy balance, making cities warmer than their hinterland and surroundings. The growth of industries and vehicles add to greenhouse gases in the atmosphere that also absorb the outgoing terrestrial long wave radiation and contribute to increasing temperatures in the city. As a result, the city center is heated up much more than the periphery, leading to the creation of UHI. UHI can be of two types—surface urban heat islands (SUHIs) and atmospheric urban heat islands (AUHIs) [1,2]. Further, AUHIs can be subdivided as urban canopy layer (UCL) and urban boundary layer (UBL). There is an abundance of research on SUHIs largely due to the dependence of data on remotely-sensed images that are freely available [3].

The introduction of remote sensing technology has motivated the large-scale researches on UHI for small and large cities of the world across continents [4]. The UHI analysis is conducted by extracting the land surface temperature (LST) using satellite-derived data. A wide range of sensors, like Landsat 4 and 5 (TM), 7 (ETM+), 8 (TIRS 1 and 2), Advanced Spaceborne Thermal Emission and Reflection (ASTER), Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), and others, are utilized for the extraction of LST [4]. The research methodologies mainly focus on the changes in LULC and associated LST changes. The studies show that there is a strong relationship between the LST and LULC [5], and hence, the creation of UHI is explored through the LULC change and LST derived from remotely-sensed images.

LULC change is the response to urbanization, where the natural vegetation areas are replaced by impervious surfaces, such as metal, asphalt and concrete [6,7]. Considering the negative impacts of this change, the expansion of urban areas and its impact on LULC have been extensively studied. To understand the influence of LULC change on the thermal environment of the urban areas, Ding and Shi [8] utilized the Landsat images of Beijing and related LULC with LST. Similarly, Jusuf *et al.* [9]

explored the consequences of LULC change on the creation of UHI in Singapore with the help of LST data. Zhang *et al.* [10] analyzed the role of LULC change and population increase on UHI patterns in Shanghai, China; while Li *et al.* [11] extracted LST and NDVI for understanding the impact of urbanization and LU change on the landscape of Shanghai. Kuang *et al.* [12,13] utilized *in situ* observations and concluded that LST differences were found for different LULC classes. They also pointed out that impervious surfaces are warmer than green areas. The LULC studies are, hence, intricately woven with LST research.

The modification of LULC associated with urbanization has altered the thermal properties of land, thereby changing the energy budget, creating the UHI [14]. LST capable of being generated from the thermal band of space borne platforms is the prime data source to map the UHI phenomenon [3]. The relationship between the spatial extent of UHI and urban factors, like urban size, development area, water proportion and mean NDVI, is presented by Zhang and Wang [15]. The seasonal variation in the formation of UHI for Delhi with the help of Landsat TM data is monitored by Singh *et al.* [16], whereas Li *et al.* [17] monitored the seasonal pattern of UHI for Shanghai in relation to surface temperature conditions and the fractional vegetation index.

Analysis and examination of the vegetation index is utilized as an indicator of the extent of LULC change. NDVI values are indicative of the degree of vegetation greenness [18]. The assessment of LULC change, UHI creation and associated transformation in NDVI using satellite images is studied abundantly. Julien *et al.* [19] conducted a temporal analysis of NDVI and LST to understand the LULC changes in Iberia using NOAA-AVHRR data. The relationship between LST and vegetation abundance for extraction of UHI for Indianapolis, IN, USA, is investigated by Weng *et al.* [4]. A similar study is conducted by Kawashima [20] for Tokyo, the Atlanta Metropolitan Area [18], Beijing [21], the Pearl River Delta, China [22], and Wuhan City, China [23], using the Landsat dataset.

Although the investigations with respect to UHI and NDVI are bountiful for major cities of the developed world, there is a paucity of research with respect to the urban areas of India. Issues pertaining to land surface emissivity, LST and NDVI are explored by Mallick *et al.* [24], Mallick *et al.* [25], Sharma and Joshi [26] and Kant *et al.* [27] for Delhi, while a UHI examination for Mumbai is still unexplored. However, analysis of population growth and LU change is examined [28], but not with the help of satellite data. Despite the fact that Delhi and Mumbai exert strong centripetal forces and are rapidly growing cities of the world, there is a scarcity of research on LULC change and the creation of microclimates. Considering the importance of the examination of UHI and NDVI, with respect to its influence in determining the microclimate and health in urban areas, it becomes an imperative area of research. Therefore, present study aims at analyzing 1) LST and UHIs patterns in Delhi and Mumbai, 2) their spatial relationships with respective NDVIs.

2. Study Area

The two largest cities of India, Mumbai and Delhi, are presented in a comparative analysis in the present study. Though the two cities vary in terms of indicators of physical and human geography, the growth with respect to population size are in contrast to each other. Delhi, located in the interior of the country, is the administrative capital of India and, therefore, is a center of a large number of executive buildings and residential areas. Mumbai, on the other hand, is a coastal city and is the financial capital of the country. It encompasses a milieu of prime financial institutions and company head offices.

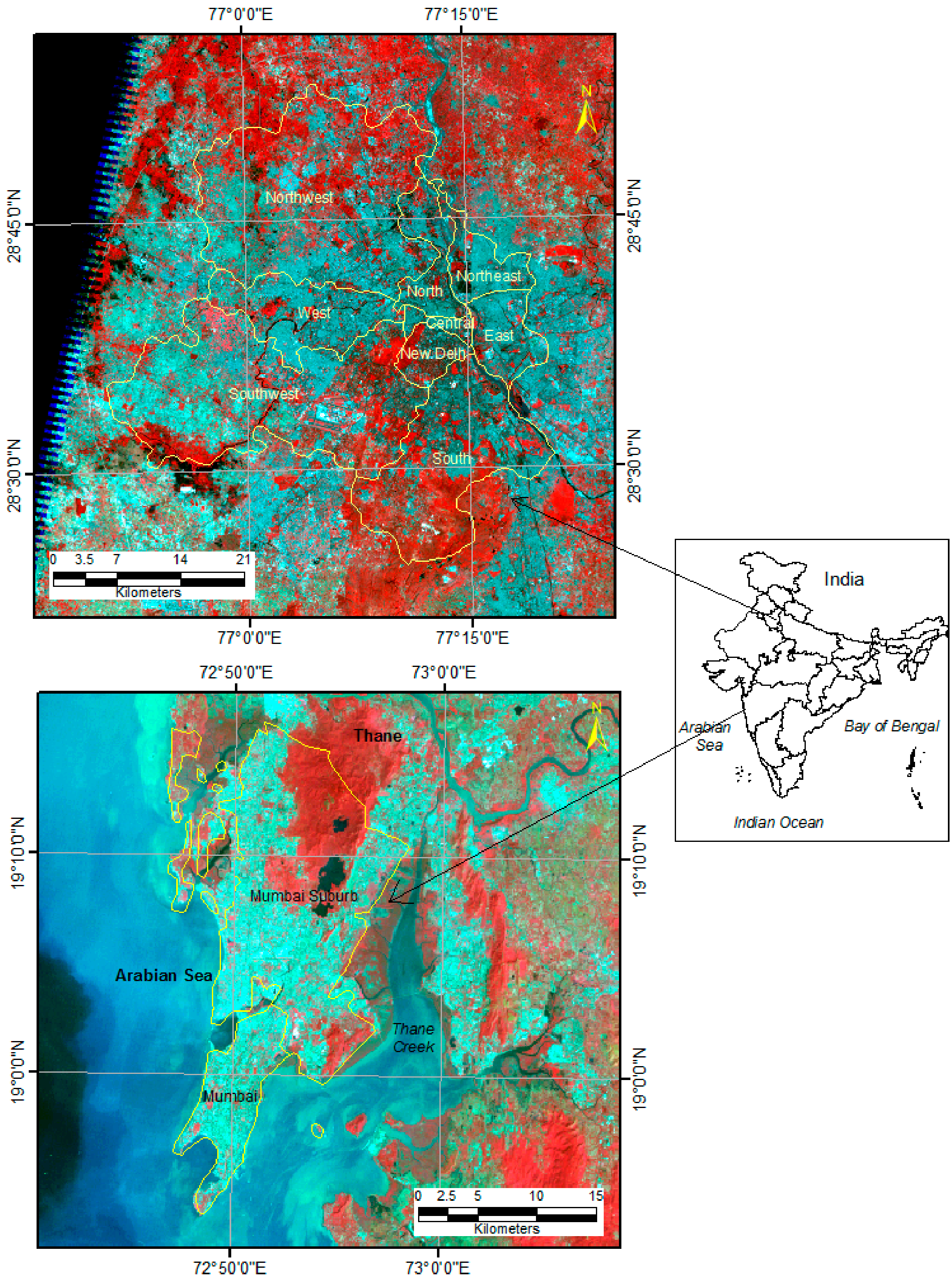

Figure 1. Location of the cities of Delhi and Mumbai in India. Landsat 5 TM images are in the background.

Delhi is located between the latitudinal extent of 28°23'17"–28°53'00" N and longitudinal extent of 76°50'24"–77°20'37" E and covers an area of 1483 km^2 with an average altitude of 213–305 m above mean sea level (msl) (Figure 1). It is bordered by Haryana in the north, west and south and Uttar Pradesh in the east. It is largely a plain area with the exception of two main physiographic features *viz*. the Yamuna River and the Delhi Ridge. The Yamuna River divides the city into two parts, popularly known as East and West Delhi. The ridge, which is an extension of Aravalli Range, borders Delhi on southern side and extends up to central Delhi. The ridge is covered primarily by thorny vegetation. The relief features act as both a thermal moderator of and cooling agent for the climate. Delhi has an extreme continental climate with annual temperature ranging from 3 °C in winters to 45 °C in June and average rainfall ranging from 400 mm to 600 mm. Mumbai is located on the west coast, *i.e.*, the Konkan coast of Maharashtra, between 18°53'–19°19' northern latitudes and 72°45'–73° eastern longitudes with an altitude of approximately 11 meters above the msl, covering a total area of 437.71 km^2. The Arabian Sea borders Mumbai to its south and west; the Thane district and Vasai Creek are in the north; and Thane Creek is on the east and southeast. Mumbai is the amalgamation of seven islands [29]. Successive reclamation of swampy and marshy lands lying between the islands has made it a large island [30].

Delhi is larger in area than Mumbai, and accordingly, it is divided into nine districts and 27 *tehsils*/sub-divisions. Mumbai over the past few decades has grown in size, and the Mumbai city district along with the Mumbai suburban district is called Greater Mumbai. The population of Delhi, according to the Census of India, 2011 [31], is 16.75 million as compared to 3,145,966 and 9,332,481 in the Mumbai city district and suburbs, respectively. The population density in Delhi is about 11,297 persons per km^2, whereas Mumbai has a much higher density of population (43,583 persons per km^2 for Mumbai city in 2006–2007 and 19,373 persons per km^2 for the Mumbai suburban district) [32].

According to the Forest Survey of India (FSI), 2011 [33], the total forest cover (176.2 km^2) and tree cover (176.2 km^2) of Delhi is about 296.2 km^2 (about 20% of the geographical area). The vegetation is mostly thorny scrub-type, representing semi-arid conditions. Mumbai, a tropical city, owing to the humid moderate climate and influence of the sea, has mangrove forests along the creeks and coast. The total area under forests cover has been estimated to be about 122 km^2, which is about 20% of the geographical area of Mumbai city and the Mumbai suburban areas [33]. Most of this is open forest, and minimal area is under moderate dense forest. Along with the sea, Sanjay Gandhi National Park, located in the Mumbai suburbs, and big lakes, e.g., Powai, Vihar and Tulsi, act as thermal moderators for Mumbai.

3. Database and Methods

The spatial patterns of LST in Mumbai and Delhi are explored and compared in relation to vegetation health, *i.e.*, NDVI and LULC pattern. The contemporary advancement in the field has encouraged the use of remote sensing data in wider issues related to the impact of the variation in LST and NDVI on human health and the urban environment. Thermal band (6th) of the Landsat Thematic Mapper 5 (TM) satellite image has been used to extract the LST, near-infrared (NIR) and red (R) for estimating vegetation health and other related information. The Landsat satellite images were acquired from the United States Geological Survey (USGS) website [34]. Since the objective is to compare the two cities, both of the images were taken from the same year and represent the same season. The respective dates of acquisition of the images are 17 April 2010 and 5 May 2010 for Mumbai and Delhi (Table 1). The Landsat image of Delhi has been also utilized in our previous study, where land use change, land surface temperature and NDVI are visually correlated [35]. In this study, we compare the two largest cities of India with the main premise of comparing and understanding the patterns of UHI, NDVI and LST with respect to contrasting physiographic and climatic conditions. Both of the cities are rapidly expanding, but are placed in different geographical settings, and therefore, the UHI analysis shows interesting results.

Table 1. Details of the satellite images used.

Satellite	Sensor	Acquisition date	Path and row	Spatial resolution*	Cloud cover
Landsat 5	TM	5 May 2010	146/040	120 m	1%
Landsat 5	TM	17 April 2010	147/047	120 m	0%

Note: * Resampled to 30 m.

To make the images in a usable form, the acquired images were pre-processed. This involved radiometric and geometric corrections. Further, three main steps were followed to extract the surface temperature from the raw image. These steps are described in the Landsat 7 Science Data Users Handbook [36], Murayama and Lwin [37] and Chander *et al.* [38]. Using Equation (1), the digital numbers were converted to spectral radiance. The spectral radiance was then converted to temperature in the Kelvin scale (Equation (2) and then to the Celsius scale (Equation (3) based on Murayama and Lwin [37].

3.1. Mapping of Surface Temperature

Step1. Conversion of the digital number (DN) to spectral radiance (L):

$$L\lambda = LMIN + (LMAX - LMIN) \times DN/255 \quad (1)$$

where $L\lambda$ = spectral radiance, LMIN = 1.238, LMAX = 15.600 and DN = digital number.

Step2. Conversion of spectral radiance to temperature in Kelvin:

$$TB = K2/\text{In}\ [(K1/L\lambda) + 1] \quad (2)$$

where K1= Calibration Constant 1 (607.76) and K2 = Calibration Constant 2 (1260.56) for the thermal band of the TM data and TB = surface temperature.

Step3. Conversion of Kelvin to Celsius:

$$TB = TB - 273 \quad (3)$$

3.2. NDVI Estimation

The NDVI in a Landsat satellite image is generated from the red (3rd) and near-infrared (4th) bands. NDVI is a widely-used vegetation index calculated using Equation (4) [4,22,23]. It appropriately represents the coverage and health of vegetation in the study area. The NDVI ranges from +1 to −1.

The positive values are representative of healthy green vegetation, while the negative NDVI values indicate non-vegetative cover.

$$\text{NDVI} = (\text{Band4} - \text{Band3})/(\text{Band4} + \text{Band3}) \quad (4)$$

3.3. Regression Analysis

System for Automated Geoscientific Analyses (SAGA) GIS software was used to estimate the regression equation between LST and NDVI of Mumbai and Delhi. All the pixels of LST and NDVI were used in the regression analysis, where NDVI was considered as the independent and LST as the dependent variable, as LST has been found to be strongly determined by vegetation health [21,39]. In most studies, the LST has been found to be negatively correlated with NDVI.

4. Results and Discussion

4.1. Analysis of Land Surface Temperature

The LST of Delhi ranges from 23 °C to 40 °C, whereas the LST of Mumbai ranges from 22 °C to 38 °C. There is not much difference in the surface temperatures, even though the location and physiography of the two cities are contradictory. In Delhi, the highest temperature is recorded in the west, especially in the southwest. The estimated surface temperature is low in the center and south, whereas moderate in the north and east. On the other hand, Mumbai has lower LST in the peripheries and along the coast and is highly heated in the center. This shows that the UHI phenomenon is not much stronger for Delhi, as for the case in Mumbai. There are multiple factors that affect the creation and intensity of the LST and UHI. These include the greenness, distribution of water bodies, impervious concrete, asphalt and metal use, LULC and surface roughness [12].

The spatial pattern of LST in Delhi shows that while the North, Central, Eastern, Southern and New Delhi districts are relatively cooler areas, the Western and Southwestern districts exhibit high temperatures (Figure 2A). The visual analysis of LST divides Delhi city into three main temperature zones: high temperature in the West, Southwest and Northwest; low temperature in the Northeast, Center, and Southeast; while moderate in between the two extremes. However, the zones are heterogeneous in nature depending on the LULC [35].

The variations in the LST distribution are noted, which exist due to the impact of the different properties of LULC. While the vegetation areas are directly related to lower surface temperatures, responsible for generating the cooling effect in the urban microclimate, concrete built-up areas add to the existing high temperatures. The perennial river, Yamuna, records minimum temperature of 23 °C, where the water depth is estimated maximum. As the quality of water changes, due to mixing of solid waste and sand, the temperature rises to nearly 28 °C. The river has relatively high heat storing and transfer capacity. It passes through six districts of Delhi and acts as a heat moderator for the city [16,40]. A similar role is played by the lakes and drains in Delhi. Even though there is a small proportion of area covered with water bodies, the spatial location of these features has a vital role in UHI creation. A dense network of drains cuts across the city to carry water and solid waste. The temperature of the drains ranges from 28–29 °C. The Najafgarh Drain is the largest drain and records a surface temperature of 27 °C in the warmest district of Delhi, *i.e.*, the Southwest district. The concrete border of the drain records a 33 °C temperature, and the agricultural fields in its vicinity have a 39 °C temperature. Apart from enhancing beauty and greenery, the natural vegetation and tree cover have a significant function of maintaining the ecological balance. The process of evapo-transpiration enables a cooling effect on the surroundings. The northern Delhi Ridge with moderate vegetative cover has a temperature ranging from 27 °C to 29 °C, depending on its density. The dense tree cover along the linear features, like the roads, has considerable influence on keeping the temperature at the lower end of the range in the surrounding regions.

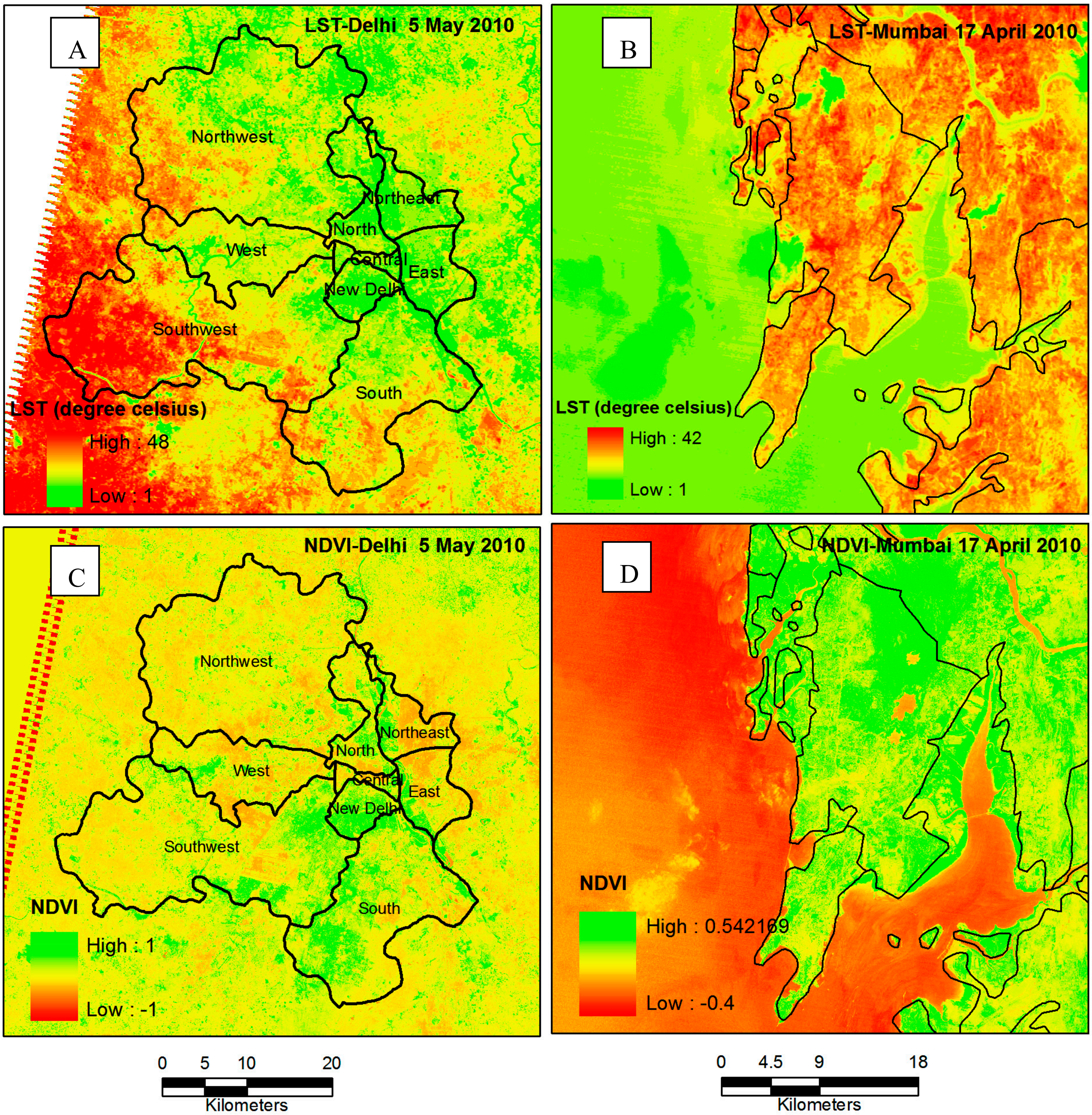

Figure 2. Comparison of the spatial distribution of LST and NDVI values in Delhi and Mumbai. (**A**) LST in Delhi; (**B**) LST in Mumbai; (**C**) NDVI in Delhi; (**D**) NDVI in Mumbai.

However, in some small fractions of land, the LST reaches 33 °C, representing intense concrete areas. Delhi is an amalgamation of both urban and rural areas. As per the census record of 2011, 97% of the population of the city is urban. Large sections of population, however, reside in rural-urban fringe areas. The expansion of the built up area in the city reiterates the increase of the urban population and the shifting of open areas and agricultural fields to the periphery. Largely, there is a 29–31 °C temperature found in the concretized areas of north, central, east and south Delhi. The highest surface temperatures for the city coincide with the agricultural land in the extreme Southwest district. In the Northwest district, highest LST corresponds to the high population density.

In Mumbai, under the influence of water and vegetative cover, lower LST than Delhi is recorded (Figure 2B). The lakes and the sea are integral factors in influencing the LST. The LST along the western coast of Mumbai is 26–28 °C and along its eastern coast, near Thane Creek, is 29–30 °C. The influence of mangrove forests and water is clearly evident from the LST values. The lakes of Virar, Tulsi and Powai are located in the Mumbai suburban district. The surface temperature for the lakes range from 24 to 26 °C. The rivers in Mumbai are small in size, and waste dumping has led to decreased water flow. Unlike the role of River Yamuna in Delhi, lesser water depth in river channels has led to the minimal impact of the river on LST.

4.2. Analysis of NDVI

The NDVI or vegetative greenness in Delhi is maximum in New Delhi and Central Delhi (Figure 2C), whereas North, Northwest and East Delhi are highly concretized and, therefore, have the least NDVI values. The NDVI values in North, Northwest and East Delhi are below −0.02, except in a few patches, which are the green areas in the dense built-up zones, which also act as breathing room. The southwest corner of the city has low NDVI owing to the presence of agricultural land. Some green areas are visible along the drain lines and around the agricultural fallow land. Further in the East is the dense amalgamation of apartments and buildings, where the tree cover along the roads, highways and open land in Delhi is more dominating than the forest cover [16]. The international airport in the south records the lowest NDVI of −0.06. On the other hand, most areas in central and New Delhi have very high NDVI, reflecting the healthy tree cover in the city. The Delhi Ridge, popularly known as the lungs of the city, and the adjoining areas of India Gate, Rashrapati Bhawan, and others have the highest NDVI. Along the banks of the River Yamuna, also, the NDVI values are relatively high, owing to the presence of agricultural land.

The NDVI values of Mumbai are relatively better than that of Delhi (Figure 2D). However, the vegetation cover in Mumbai city is much lower than the suburban areas. The dense built-up areas and intense road and railway network have influenced the NDVI of Mumbai. Owing to the imbalance in the built-up and natural land cover, eastern Mumbai city has largely negative NDVI values. A small patch of high NDVI of 0.2 to 0.4 is found near Colaba Point (Figure 2D). Other prominent green patches of NDVI ranging from 0.2 to 0.5 correspond to Shastri Nagar-Trombay and Worli-Tardeo in Mumbai city. The coastal areas of the eastern coast along the Gateway of India and in the west beside Nariman Point and Back Bay record low vegetation cover. The thickly populated and concrete zones in the city possess a vegetative index below 0.06.

In contrast to south Mumbai, the northern suburban district is much greener. Ghatkopar, Vikhroli, Bhandup and Mulund along Thane Creek in the eastern coast record NDVI of 0.2–0.3. The mangrove forests are prominent feature of this region. Further, in the central and northern suburbs, Sanjay Gandhi National Park dominates the region. NDVI values depend on the density of trees and greenness and, therefore, range from 0.3 to 0.54. The maximum NDVI of 0.5–0.54 is found in small patches corresponding to Sanjay Gandhi National Park in Powai and Borivilli and mangrove areas alongside Manori Creek. The western coast from Versova to Gorai has comparatively higher NDVI than the southern coast. Yet, the impact of urbanization is low in northwestern Mumbai and the extreme northeastern suburbs, and therefore, the vegetation is higher than south Mumbai.

Mumbai is an island city surrounded by the sea and creeks on three sides. Mumbai is an amalgamation of seven islands, and the result of reclamation done by the British during colonial rule. Mumbai city has grown as a result of large-scale immigration and has swelled to form the Mumbai suburbs. Due to the expansion of the manufacturing sector, especially in trade and textile mills, the island soon emerged as a Central Business District (CBD). The major forces underlying this growth of Mumbai are its role as a financial hub and a well-linked transportation network that facilitates the export of finished products. The city flourished and enjoyed the status of a CBD for a long time. However, due to added pressure, the living conditions deteriorated, profits from mills reduced and, therefore, the role and value of the CBD declined. However, it still remains the center for the headquarters of all government and private organizations. Later, a new CBD has been initiated at Nariman Point [29]. The density of Mumbai city is much higher than Delhi. There is crunch of space in the city, and as a result, the Mumbai suburbs are swiftly urbanizing. Distant places in and around Mumbai are well connected by roads and railways. The combination of increased land prices in the city and a good transport network to the city has facilitated the movement of people to the suburban areas. The growth of the city, however, has led to countless changes in LULC, initiating LST alterations.

The dependency between the LST and NDVI for the two cities is represented by regression analysis (Figure 3A,B). In the case of Mumbai, 36% of the relationship is explained by NDVI, which indicates that the lower vegetation index is responsible for the LST patterns. On the other hand, only 6.37% of the dependence is reflected in Delhi. This states that there are other possible reasons for the high temperatures in Delhi. This could be the presence of aerosols, as pointed out by Pandey *et al.* [41]. The impervious nature of LULC class and surface roughness also has a role to play in the UHI creation [11,42]. These can be other possible causes of pockets of high temperature found in Delhi.

5. Conclusions

Delhi and Mumbai contrast each other with respect to location, climatic conditions and the nature of urban growth. The two largest cities of the country have undergone a differential sort of urbanization process. In Mumbai, the daily movement of people from nearby districts is much more prominent than Delhi. Mumbai also has a larger number of high rises than Delhi. The concrete land in Mumbai is greater than in Delhi. The agricultural land has diminished over the years and also has been shifted to the periphery, but it is to be noted that in Delhi, agricultural activities do persist. In contrast, the economy in Mumbai is largely secondary and tertiary sector dependent. All of these factors signify that the nature of urban development in the two cities is dissimilar. This is reflected in the UHI formation, whereby in Mumbai, there exists strong UHI, but this is weak for Delhi. The regression analysis between LST and NDVI proves that Delhi has a larger area under green cover, and hence, the UHI effect is diminished. In Mumbai, the absence of tree cover along with other factors has led to increased LST. In this scenario, it becomes imperative to focus on a stricter implementation of urban planning norms and to stress increasing green cover in the cities.

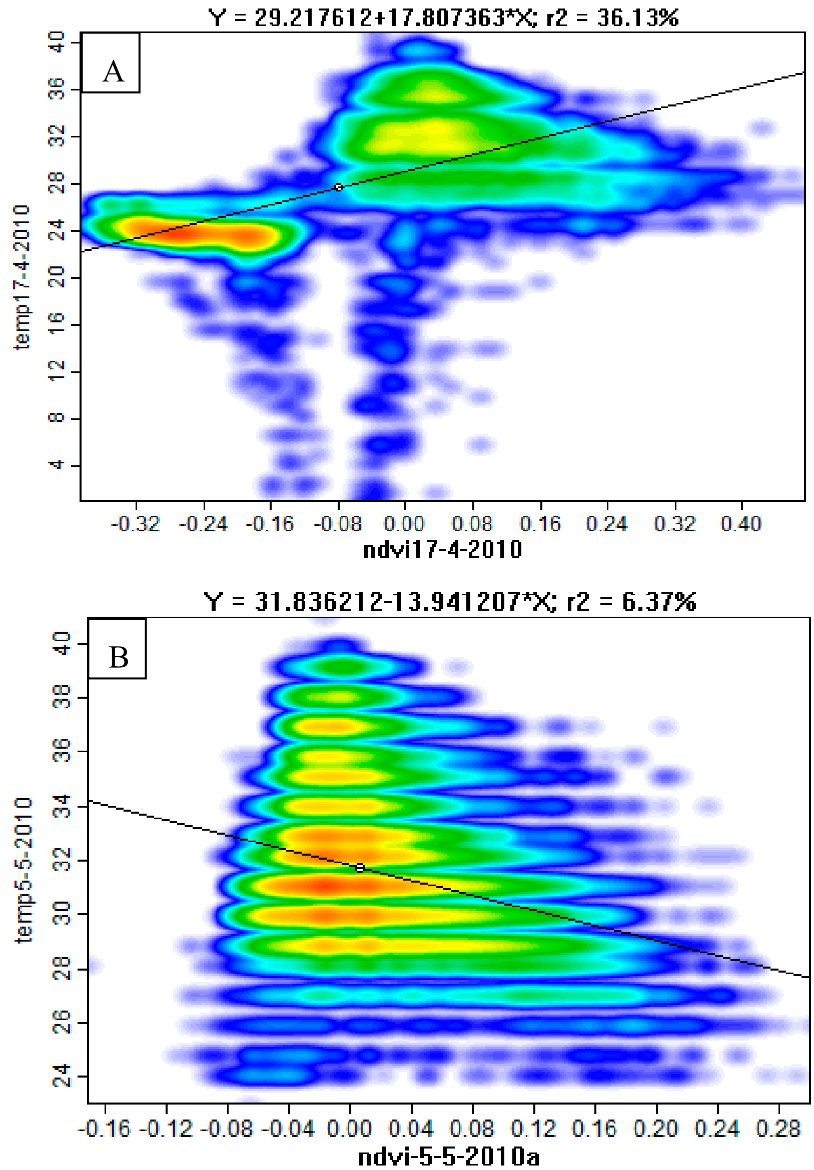

Figure 3. Regression analysis of LST and NDVI, where NDVI is the independent and LST is the dependent variable. (**A**) Scatter plot for Mumbai and (**B**) for Delhi.

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Author Contributions

Aakriti Grover carried out the analysis, drafted and revised the manuscript. Ram Babu Singh had the original idea and drafted the manuscript. Both the authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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