RESEARCH PAPER

PREDICTING THE IMPACT OF LAND USE CHANGES ON THERMAL ENVIRONMENT IN LAHORE, PAKISTAN: IMPLICATIONS FOR URBAN PLANNING

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ABSTRACT. Land use changes significantly threaten urban areas, especially in developing countries such as Pakistan, impacting the thermal environment and comfort of human life. The ongoing transformations in cities such as Lahore, the second largest and rapidly expanding urban center in Pakistan, are alarming due to the removal of green cover and the disruption of ecological structures. In response to these concerns, this study was conducted to assess and predict the implications of observed land use changes in Lahore. The analysis employed three Landsat images from 1990, 2005, and 2020, using ArcGIS and Idrisi Selva software. The results show that the built-up area increased almost 100% (16.44% to 32.48%) during the last three decades. Consequently, a substantial shift from low to medium and medium to high degrees of LST was observed. The projections indicate a further 50% expansion of the built-up area, encroaching upon green cover until 2050, shifting more areas under a higher LST spectrum. So, the study concludes that Lahore is facing imminent threats from rapid land use changes caused by higher land surface temperature in the study area, necessitating prompt attention and decisive action. The study area is at risk of losing its conducive environment and the desirable uniformity of the thermal environment. Therefore, it is recommended that green cover be strategically enhanced to offset the rise in built-up areas and ensure a sustainable thermal environment.

KEYWORDS: Land Surface Temperature; Land Use Changes; Urban Green Cover; Thermal Environment; Urbanization

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INTRODUCTION

Urbanization is one of the most critical human-caused changes to land use and land cover (LULC) on the earth (Gallo and Owen 1999; Guo 2015; Zhao et al. 2020). Land use and land cover changes are essential when studying global dynamics and how they respond to thermal environments and socio-economic factors (Zhao et al. 2020). A growing global environmental concern is the changes in land use and land cover and how they affect Land surface temperature. Although "land cover" and "land use" may be used interchangeably, they have different meanings. The term "land use" describes how land is used for various objectives, including housing, agriculture, education, and recreation. In contrast, land cover describes the kinds of covering on the earth, such as water, bare rock, or forests (Anderson 1976; Zhang et al. 2019; Siddique et al. 2020). LULC are highly significant for managing the urban environment, heterogeneity of landscapes, human life functions, and socio-economic activities (Schott 2007). Urban greenness has appeared significant for understanding, managing, and enhancing its multiple services under the highly fragmented urban landscapes affected by rapid urbanization (Benedict & McMahon 2012; Hanif et al. 2022). Therefore, balanced urban landscapes are highly significant for a sustainable urban environment where green spaces are vital for ecological services (Nasar-u-Minallah et al. 2023). It has been analyzed that green cover in an urban area is increasingly uneven due to the rapid increase in unplanned urbanization. The availability of green spaces currently does not meet the requirements of suitable landscapes for human beings (Ernstson 2013; Wolch et al. 2014). Therefore, the importance of green spaces with their spatial distribution and functioning has increased, and it has been accepted that every element of the green landscape has its specific importance. For instance, trees have more cooling effects than a grassy landscape, but the grassy landscape may be more effective for its aesthetic values (Jabbar et al. 2021; Jabbar & Yusoff 2022). Assessing inequality in urban landscape settings can improve land usage and environmental status.

LULC change analysis provides valuable and essential information for several applications in the geospatial field. Environmental management and monitoring urban and regional planning are prime examples (Bhalli and Ghaffar 2015; Liu et al. 2017; Zhang et al. 2019; Zia et al. 2022). The information produced by land use changes can also be used for socio-economic challenges, climate change effects, food security, and disaster risk management (Stürck et al. 2015). Land use mapping on satellite-based data provides up-to-date information on Earth surface changes. Accordingly, multi-temporal analysis of land use changes can be monitored in land surface dynamics (Hansen et al. 2013; Nasar-u-Minallah et al. 2021) and urban growth (Taubenböck et al. 2012; Minallah et al. 2016). LULC change predictions are a process through which we can estimate the future scenario of any area for future planning to avoid its adverse consequences. As such, several studies use a variety of approaches for LULC change predictions. The approaches vary based on their purposes, location, methodologies, source of data, and type (Michetti & Zampieri 2014). The Markov chain system uses chain analysis techniques to predict land use changes (Eastman 2006). The land use planning of urban areas should be approached according to the socio-economic and physio-ecological attributes that may be present. Vegetation on a landscape increases its socio-economic value, and land-use changes collectively affect the environment and economy (Riaz et al. 2017; Fu et al. 2018). Sustainable development in a compact city is also related to the price of land, and many researchers have used three dimensions of sustainability (social, economic, and environmental) during land-use studies (Gonzalez-Redin et al. 2019; Parveen et al. 2019).

The presence of urban green spaces (UGSs) and their spatial distribution is essential for assessing and measuring their expected impacts on human beings and the city environment (Kuo et al. 2011). A standard number of UGSs required to sustain an ecologically healthy environment for human beings can be judged under World Health Organization (WHO) guidance. The standard set by WHO is 9 m^2 per person, which is the minimum benchmark per person (UN-Habitat 2013). Availability typically refers to the quantity of UGSs in an urban area, whereas accessibility indicates the location and distance humans must travel for green space. The term accessibility in this context refers to the spatial nearness of UGSs for humans (Koohsari et al. 2015). The existence and ease of access to green spaces have been outlined and evaluated under spatial equity matters (Zhou et al. 2017). It has been demonstrated that UGSs, such as parks enhance active lifestyles, mental health, and social cohesion.

The availability of open or green spaces for humans also contributes to more dynamic behavior, social responsibility, and care for public resources. It improves inhabitants' co-existence, tolerance, health, and quality of life (Ward 2013; Jabbar & Mohd Yusoff 2022). The accessibility and vegetation structure, location, shape, and scale are vital in recreational activities and ecological resources. If an urban green space has more potential for recreational facilities, it will be considered a more attractive place for children and parents (Lachowycz & Jones 2013). Thus, urban green spaces play a pivotal role in fostering sustainable cities by offering diverse benefits to both human and animal populations. Scientists emphasize their significance in regulating the environment and enhancing socio-economic values. However, a critical need arises to quantify the requisite green area for a specific population. Concurrently, the escalating conversion of green cover into built-up environments in rapidly urbanizing cities exacerbates challenges, such as heightened temperatures and urban heat islands (Gull et al. 2019). Lahore, the second most populated city in Pakistan, is currently undergoing rapid land use changes, and the absence of robust environmental regulations intensifies the conversion of green spaces in the city context (Jabbar et al. 2023; Nasar-u-Minallah 2018). This ongoing transformation poses environmental and socio-economic concerns, warranting a comprehensive scientific assessment.

This study aims to ultimately assess and predict the impact of land use changes on the thermal environment of Lahore until the year 2050. The significance of this research lies in its potential to inform evidence-based urban planning strategies, addressing the implications of land use changes on thermal dynamics. By scientifically examining the trajectory of these changes, the study can extract and contribute valuable insights for sustainable urban development in Lahore. However, it is essential to note that limitations and gaps in the existing literature may influence the study outcomes. These could include data constraints, variations in methodologies, and the dynamic nature of urban systems. Acknowledging and addressing these limitations enhances the robustness of the study. The study hypothesizes that the ongoing land use changes in Lahore will substantially increase built-up areas, contributing to elevated temperatures and urban heat islands. The lack of environmental regulations exacerbates these challenges. The study aims to provide quantifiable projections and insights through scientific analysis, hoping to ultimately facilitate informed urban planning decisions to mitigate the adverse impacts on the thermal environment.

MATERIALS AND METHODS

The Study Area

Lahore, located in the Punjab province of Pakistan on the bank of the river Ravi, has been chosen as the focus area of this study. As the second largest metropolitan city in Pakistan in terms of population, it faces significant and unique environmental pressures that are relevant to the study. With a population of 13.98 million people (GOP 2023) and a density of 6278/km^2 (GOP 2017), Lahore is the most rapidly growing city in Pakistan and covers an area of 1,772 km^2 and located between 31° 15′ to 31° 45′ N and 74° 01′ to 74° 39′ E. The city is divided into ten administrative units, as shown in Figure 1. The research area's climate is semi-arid, with five distinct seasons: (i) a foggy winter with some rainfall from western depressions from mid-November to mid-February; (ii) a pleasant spring from mid-February to mid-May; (iii) a warm and humid summer with dust and rainy storms from mid-May to end-June; (iv) a rainy monsoon from July to mid-September; and (v) dry autumn from mid-September to mid-November. In Lahore, June has the highest temperature, July the wettest, and January the lowest, with an annual maximum of 48.3°C and a minimum of -2.2°C, as illustrated in Figure 2.

As a vibrant and historically rich city, Lahore boasts a diverse socio-economic and physio-environmental setup reflecting the dynamic tapestry of urban life. On the socio-economic front, Lahore stands as a bustling economic hub with a thriving business community, diverse industries, and a robust informal sector. Its cultural richness is mirrored in the plethora of markets, heritage sites, and a lively street life that characterizes its social landscape. Simultaneously, the physio-environmental aspects of Lahore present a complex urban scenario. The city faces rapid urbanization, characterized by an expanding population, extensive land use changes, and the conversion of green spaces into built-up or industrialized areas. These transformations contribute to challenges such as rising temperatures, urban heat islands, heavy waves, and smog, necessitating a nuanced approach to balance economic growth with environmental sustainability in Lahore evolving urban fabric.

Data Acquisition and Pre-preparation

The Landsat images were acquired using the Path/Row 149/38 from the Earth Explorer website (https://earthexplorer.usgs.gov/). The spring season was selected to acquire Landsat images due to the fully green cover and the ideal land use classification time. Therefore, based on availability and clear weather conditions, the study obtained Landsat images from March 16, 1990, April 2, 2005, and March 18, 2020. All the images obtained have a resolution of 30 meters, and they are sensed by different sensors at different times; the details are provided in Table 1. After band composition, the study area was extracted by applying the "extract by mask" function in ArcGIS.

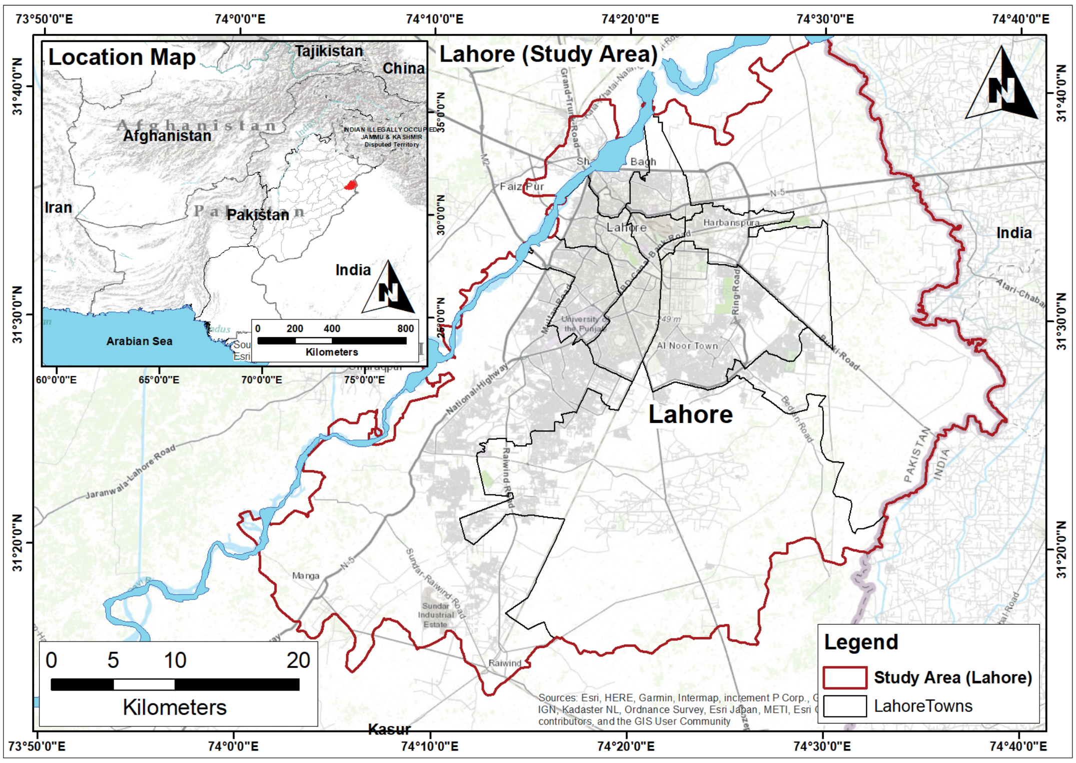

Fig. 1. Geographical Location of the Study Area (District Lahore)

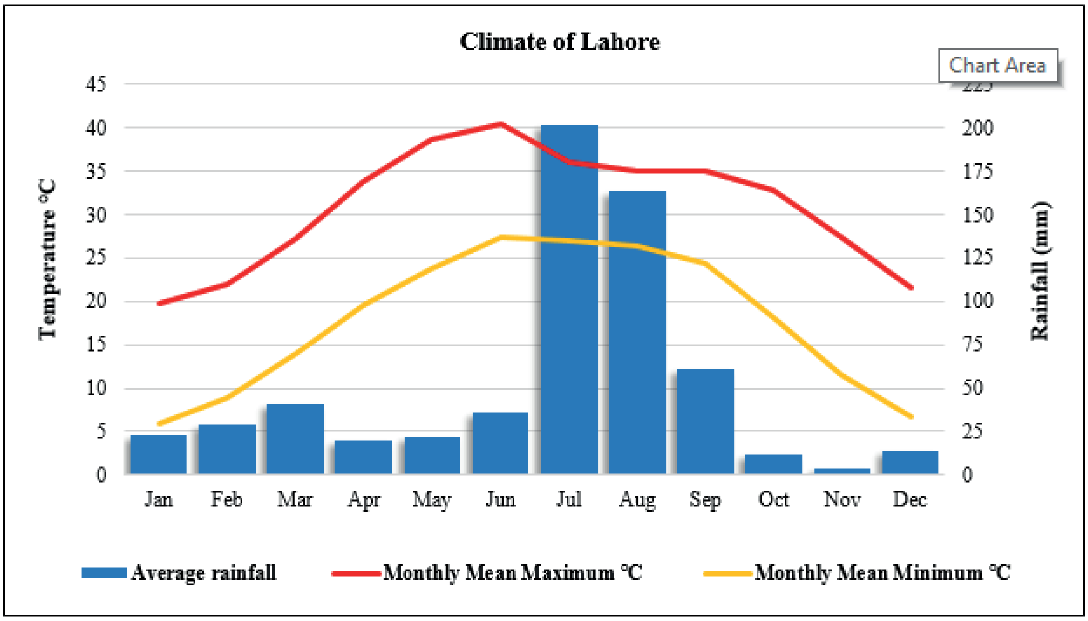

Fig. 2. Climate of the Study Area (District Lahore)

Table 1. Landsat Image Characteristics Used in the Study

Years	Satellite	Sensor	Path/Row	Resolution (m)	Acquisition Day
1990	Landsat-5	TM	149/38	30	16-03-1990
2005	Landsat-7	ETM+	149/38	30	02-04-2005
2020	Landsat-8	OLI/TIRs	149/38	30	18-03-2020

LU/LC Classification

The study utilized the supervised image classification technique to classify the study area. Supervised image classification is a well-recognized Landsat image classification technique aimed at achieving maximum accuracy (Anwar and Bhalli 2012; Bhalli et al. 2012a; Bhalli et al. 2012b; Barman et al. 2016; Iqbal & Iqbal 2018; Naeem et al. 2021; Mazhar et al. 2023). Four main land use classes are used to categorize the research area: bare land, built-up area, green cover, and water bodies.

Accuracy Assessment

The accuracy of the classified images was assessed by generating 450 random reference points. The following equations were applied in this process, and the obtained accuracy is presented in Table 2.

$$Producer'\ Accuracy\ (\%) = \left(\frac{x_{kk}}{x_{+k}}\right) \times 100 \quad (1)$$

$$User'\ Accuracy\ = \left(\frac{x_{kk}}{x_{k+}}\right) \times 100\,\% \quad (2)$$

$$Overall\ Accuracy\ (OA) = \frac{1}{N} \sum_{k=1}^{\gamma} n_i \quad (3)$$

$$Kappa - coefficient\ (k) = \frac{n \sum_{k=1}^{r} x_{kk} - \sum_{k=1}^{r} (x_{k+} \cdot x_{+k})}{N^2 - \sum_{k=1}^{r} (x_{k+} \cdot x_{+k})} \quad (4)$$

LU and LC Change Detection

The study employed a post-classification comparison approach to identify changes between two classified images. Similarly, three self-classified images were used to detect LULC changes during the study period (Bhalli et al. 2013a; Bhalli et al. 2013b; Bhalli et al. 2012b). The change (C) in land use classes was calculated using Equation 5.

$$C_i = L_i - B_i \quad (5)$$

Next, using equation 6, the study determined the percentage of changes in land cover (C%).

$$Pi = (Li - Bi) / Bi \times 100 \quad (6)$$

Computation of LST

For Landsat-5 and 7

Chen et al. (2002) state that band 6 for Landsat 5 and 7 is used in the investigation to measure LST. First, the study used equation 7 to transform the digital numbers (DNs) of band 6 into radiation luminance. In this equation, LMAX and LMIN have values of 1 and 255, respectively, while QCALMIN has a value of 1 and QCALMAX has 255. QCAL represents DN.

$$Radiance = \frac{LMAX - LMIN}{QCALMAX - QCALMIN} (QCAL - QCALMIN) + LMIN \quad (7)$$

Secondly, the LST was calculated in Kelvin using equation 8.

$$T = \frac{K2}{In\,(K1/L\gamma + 1)} \quad (8)$$

Lastly, 'Kelvin (A)' temperature values were converted into 'Degree Celsius (B)' using equation 9.

$$B = A - 273.15 \quad (9)$$

For Landsat 8

The following metadata values were applied to Landsat 8 images for LST in the study: In terms of Radiance, add bands 10 and 11, which have 0.10000, 0.0003342 for Radiance Mult Band 10 and 11, 774.8853 for K1 constant band 10, 1321.0789 for K2, 480.8883 for K1 constant band 11, and 1201.1442 for K2. The Landsat 8 LST in five phases using the values mentioned above:

(i) Equation 10 was used in the study to transform thermal infrared digital numbers into TOA (Top of Atmosphere) spectral radiation.

$$L\lambda = ML \times QCAL + AL \quad (10)$$

(ii) Spectral radiance data were converted into TOA brightness temperature using equation 11.

$$BT = K2 / In\,(k1/L\lambda + 1) - 272.15 \quad (11)$$

(iii) NDVI was calculated using equation 12 and suggested by Shah et al. 2022.

$$NDVI = NIR - RED / NIR + RED \quad (12)$$

(iv) Average Land Surface Emissivity (LSE) was calculated using equations 13 and 14, in which PV shows the proportion of vegetation, and E shows Land Surface Emissivity.

$$PV = (NDVImax - NDVImin / NDVImax + NDVImin)\ \hat{}\,2 \quad (13)$$

$$E = 0.004 \times PV + 0.986 \quad (14)$$

(v) LST was calculated by using the following equation 15.

$$LST = (BT/1) + W \times (BT/14380) \times In\,(E) \quad (15)$$

The areas of each LST range were computed in QGIS 3.14, creating the LST maps.

Table 2. Accuracy of classified images

	1990		2005		2020	
Class Name	UA	PA	UA	PA	UA	PA
Barren Land	89.83%	88.13%	86.91%	88.23%	93.21%	90.25%
Built-up Area	83.08%	90.01%	88.41%	86.76%	90.36%	93.35%
Green Cover	90.65%	88.81%	92.14%	94.65%	93.57%	93.54%
Water Bodies	91.92%	100%	100%	100%	100%	100%
	OA = 87.76% KC = 0.83		OA = 90.57% KC = 0.87		OA = 92.76% KC = 0.91	

Note: UA = User's Accuracy, PA = Producer's, OA = Overall Accuracy, KC = Kappa-coefficient

Quantification of NDVI and NDBI

Equation 12 was used to quantify NDVI, while Equation 16 was utilized to quantify NDBI, as suggested by Shah et al. 2022.

$$NDBI = (SWIR - NIR) / (SWIR + NIR) \quad (16)$$

Next, using Fishnet Polygons to extract data from LST, NDVI, and NDBI maps, the correlations between LST and NDVI and NDBI were examined.

Prediction of Land Use/Land Cover

LULC change prediction analysis was conducted in IDRISI software (version 17), utilizing the CA-Markov Model. The model integrates cellular automata and the Markov chain to forecast future LULC (Tegene 2002; Yang et al. 2014). For LULC change prediction analysis, LULC maps of 1990 and 2005 served as inputs for transition probability images. The CA-Markov model simulated the land use and land cover map for 2020, and a transition suitability image was generated by applying a multi-criteria evaluation model. Subsequently, a cross-classification between the predicted map of 2020 and the detected map of 2020 was analyzed, as shown in Figure 3. Finally, LULC prediction maps for 2035 and 2050 were generated using transition probability images.

Prediction of Land Surface Temperature

LST prediction analysis was carried out using the MOLUSE Plugin in QGIS 2.18. This Plugin operates based on an artificial neural network (ANN), a widely accepted method for predicting LST (Imran & Mehmood 2020; Alam et al. 2021; Fattah et al. 2021; Jafarpour Ghalehteimouri et al. 2022). Figure 4 illustrates the architecture of the LST prediction model.

RESULTS AND DISCUSSION

Land use Changes (1990 – 2020)

LULC classification of the study area for 1990 is depicted in Figure 5(A), revealing that bare land accounted for 13.77%, built-up area for 16.44%, Green Cover for 66.04%, and water bodies for 3.75%. Thus, in 1990, the study area boasted nearly two-thirds green cover, rendering it an environmentally friendly urban space in Pakistan, often

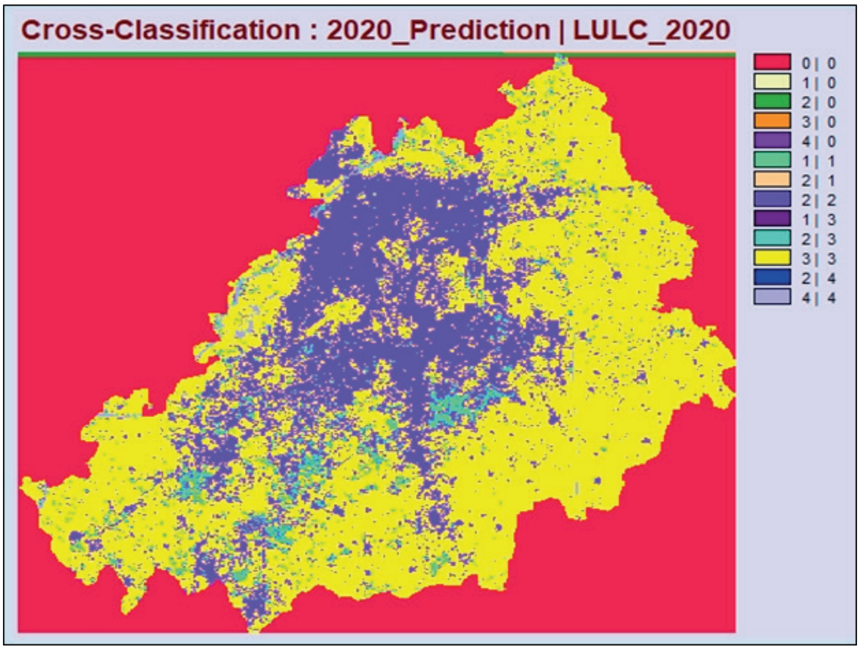

Fig. 3. Cross-classification of Images

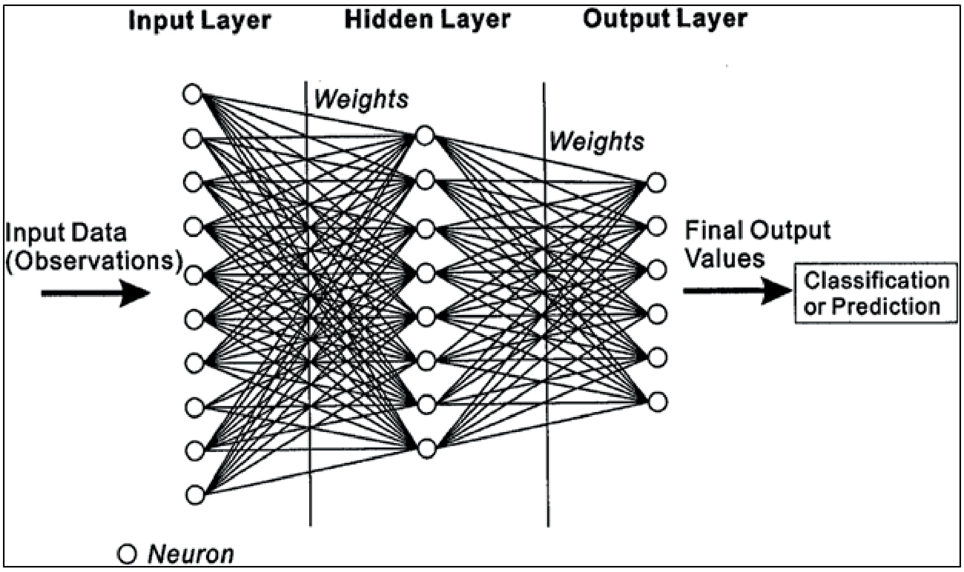

Fig. 4. LST Prediction Model Architecture

referred to as the city of gardens. Similarly, Figure 5(B) illustrates the LULCs of the study area for 2005, indicating Bare Land at 13.20%, built-up Area at 20.65%, Green Cover at 62.68%, and Water Bodies at 3.52%. Furthermore, Figure 5(C) displays the LULCs for 2020, wherein Bare Land occupied 4.04%, built-up area 32.48%, Green Cover 60.86%, and water bodies 0.68%. The area covered by all land types for 1990, 2005, and 2020 is presented in Figure 5(D). According to 2020 data, Lahore boasted a green cover area of 12.98 m^2 per person across the entire district. However, this value is anticipated to decrease due to current land use patterns.

Land Use Gains and Loss (1990 – 2020)

Gains and losses of the land use are evident in Figure 6, facilitating easy comparison. It reveals that bare land lost over 200 km^2 and gained nearly 50 km^2 of the area. Similarly, built-up areas experienced a gain of almost 400 km^2 while only losing 90 km^2. Green cover saw an increase of almost 220 km^2 but also suffered a loss of nearly 300 km^2 of its area. Similarly, water bodies gained nearly 10 km^2 but lost 60 km^2 of their area.

The net change in land use of the study area is illustrated in Figure 7, highlighting the significant area lost by bare land and gained by the Built-up area. Similarly, green cover and water bodies also experienced almost equal losses. While the "Gains and Losses of land covers (1990 - 2020)" section visually depicts the rates of loss and gain of classified land types, it is understood that readers may desire a more detailed understanding of the specific land cover classes contributing to the observed increases. The study indeed delves into this aspect, examining the percentage ratio of classes that have transformed into built-up areas, water bodies, and other categories.

The rapid growth of built-up areas is a significant concern of the study and the developing world in general because it accelerates several environmental issues. Urbanization is an essential feature of human development that directly affects urban ecology and ecosystem services (Larson et al. 2016). The rapid urban expansion puts pressure on biodiversity and other ecological patterns of urban landscapes (Song & Wang 2015; Nasar-u-Minallah et al. 2023). An increase in the population of urban areas demands more ecological services due to urban expansion.

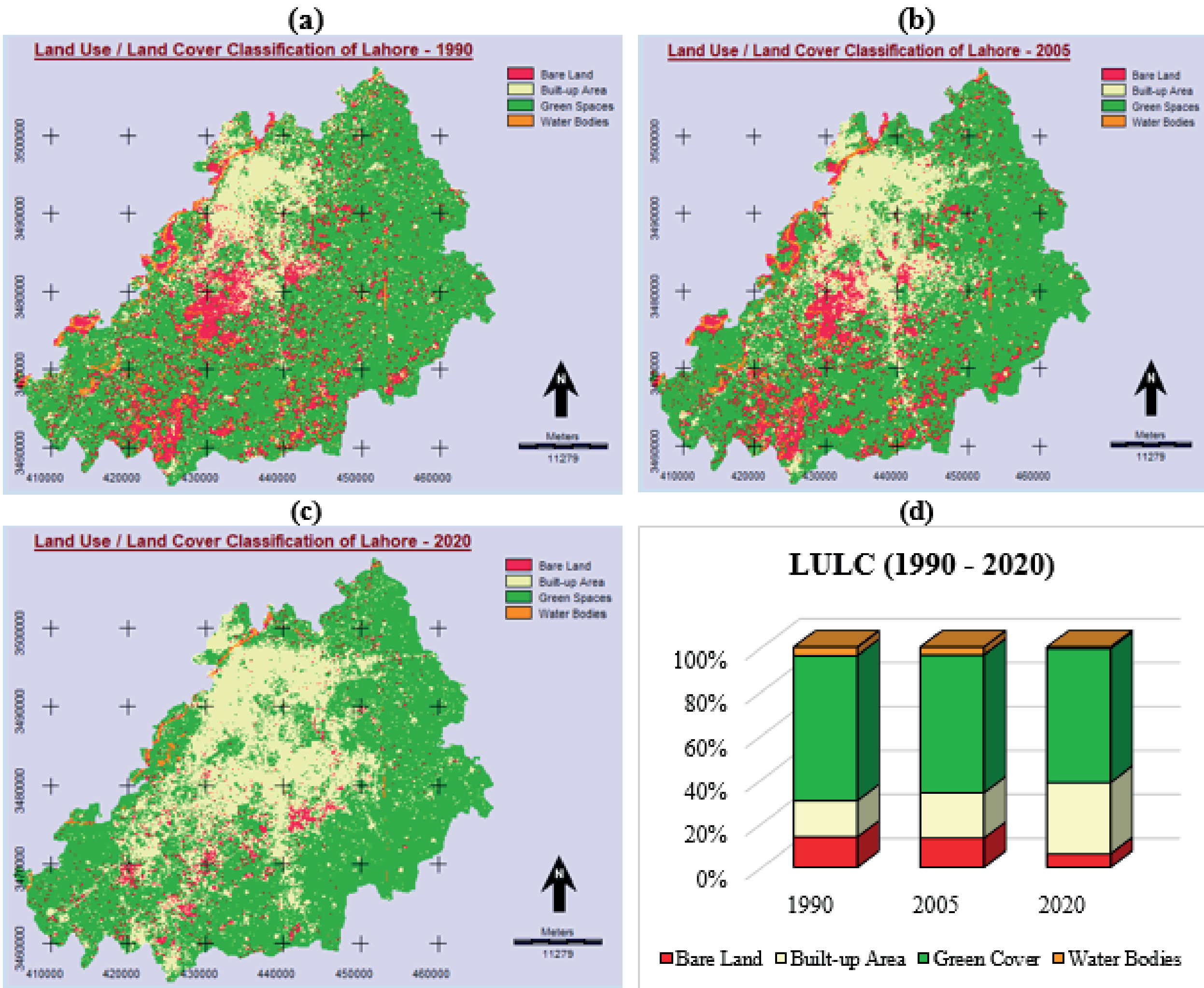

Fig. 5. Observed Land Use Changes in Lahore from 1990 to 2020

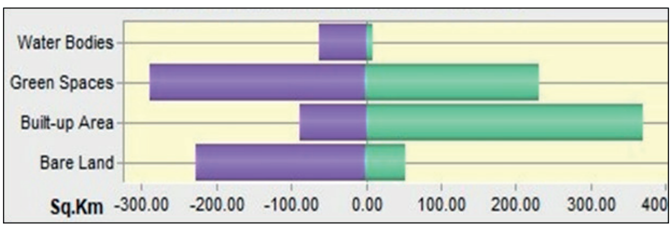

Fig. 6. Land Use Gain and Loss from 1990 to 2020

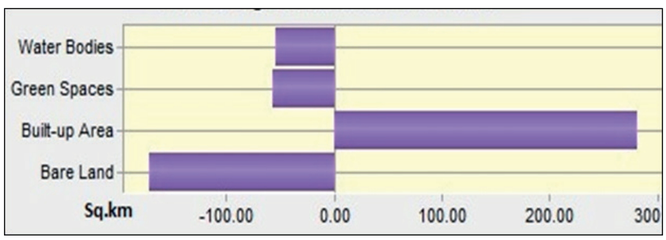

Fig. 7. Net Change in Land Use from 1990 to 2020

The ecological carrying capacity of UGSs has been reduced by urban population pressure (Daneshvar et al. 2017; Hanif et al. 2023). Land use changes pose severe challenges for urban management due to their significant ecological resource effects (Mustard et al. 2012). Therefore, studying land use changes is essential for effectively managing natural and environmental resources (Thilagavathi et al. 2015). The study area suffers from severe environmental issues due to decreasing UGSs and increasing built-up areas. The results demonstrate that the ratio between green and built-up areas was almost 71:29 in 1990, which was found to be 49:51 in 2020 after a 22.17% loss of green areas in 2020. So, 22.17% of the study area has been transformed from green to built-up areas, which may accelerate environmental issues.

Forests also play a critical role in the livelihoods of millions of individuals and are a significant contributor to the national economic growth of many countries. Forests are essential for carbon sinks and contribute to climate change rates, soil development, and water control. The forestry industry also has direct employment estimated at 10 million people (FAO 2010). Apart from providing livelihoods for millions more, approximately 410 million people depend on forests for their livelihood and income, with 1.6 billion people relying on forests for a living (Köhl et al. 2015). Research conducted by UNEP, FAO, and UNFF (Köhl et al. 2015) found that the world forests have declined due to a growing human population. Unfortunately, in the last 50 to 100 years, the deforestation rate (0.5%) has risen significantly in emerging nations.

Predicting LULC Changes (2020 – 2050)

LULC changes will be one of the significant reasons for future challenges for the study area because the last 30-year trend shows a rapid expansion in built-up areas by removing the green spaces. Therefore, the study projected an LULC classification of the study area for 2035, as shown in Figure 9, which shows that the study area will consist of 3.30% bare land, 40.09% built-up areas, 56.13% in green spaces, and 0.49% in water bodies. The continuation of the current LULC changing trend will also accelerate current environmental issues. Thus, the study projected LULC classification for 2050 (Figure 10), showing that the study area will contain 2.44% bare land, 51.73% built-up area, 45.47% green spaces, and 0.37% water bodies.

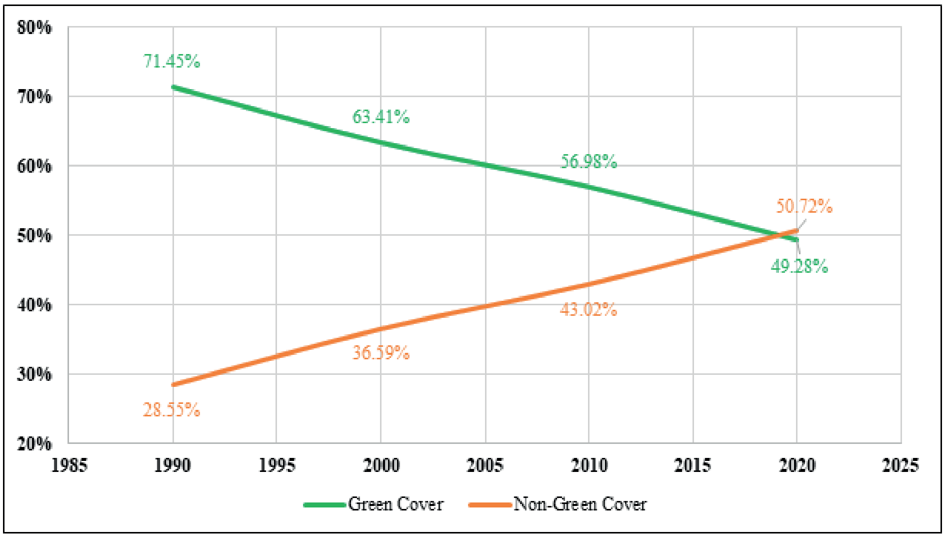

Fig. 8. Changes in Green and Non-green Covers in Lahore from 1990 to 2020

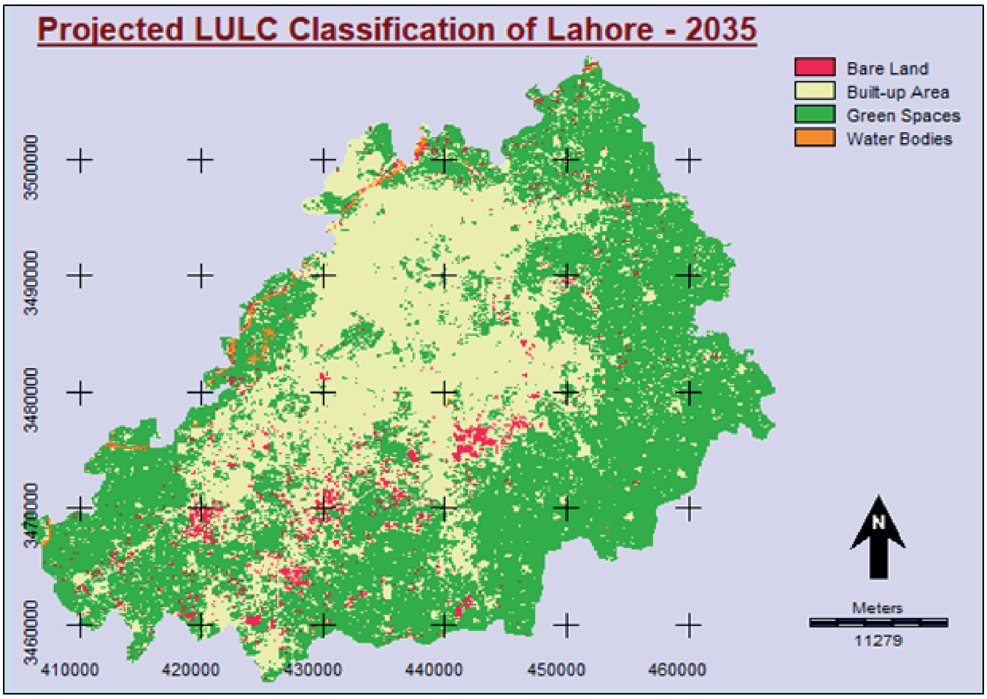

Fig. 9. Projected Land Use of Lahore in 2035

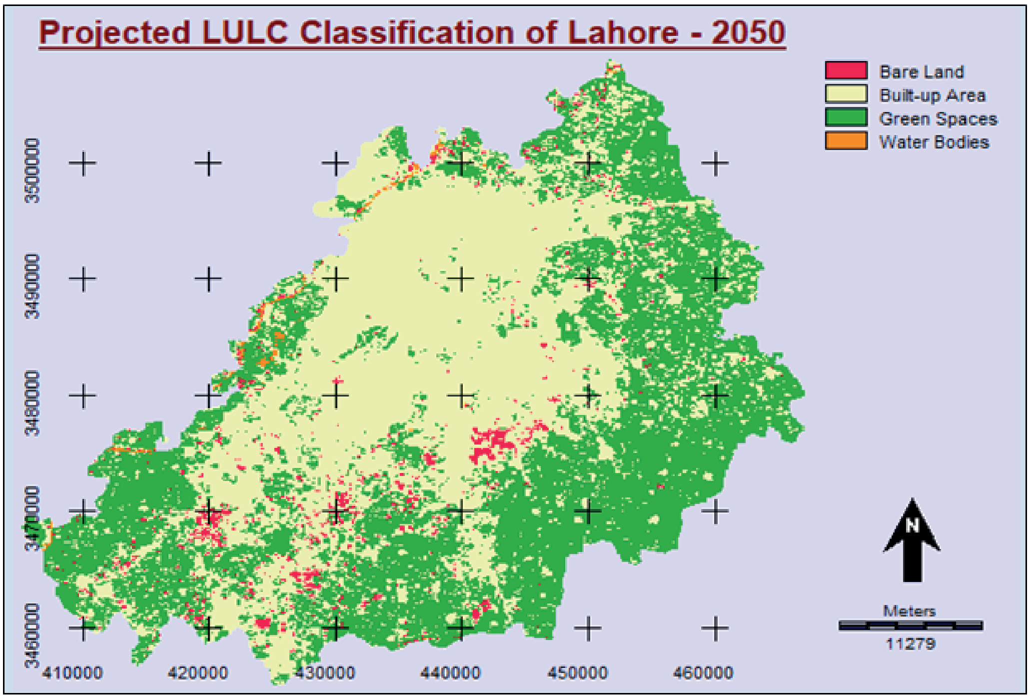

Fig. 10. Projected Land Use of Lahore in 2050

The LULC of the study area from 1990 to 2020 (observed) and 2020 to 2050 (predicted) are shown in Figure 10. It has been analyzed that green spaces are shrinking rapidly, whereas built-up areas are expanding rapidly (Figure 11). So, this change in land use will reduce the number of green spaces from 60.86% (2020) to 45.51% by 2050. Similarly, the expanding trend of the built-up area will increase over 51.76% from 32.48% (2020) till 2050. Moreover, the decrease in bare land and water bodies will continue, and both landforms will be found at 2.45% and 0.34%, respectively, till 2050.

Figure 12 displays the anticipated increases and decreases in land cover types within the study area. The figure shows that the maximum loss (more than 300 km^2) will occur in green spaces, whereas the maximum gain will occur in the built-up areas of the study area. Therefore, it is projected that they will expand at the expense of green areas in the future, which is a significant concern. Similarly, Figure 13 shows the net change in land covers, where it can also be seen that a significant net change will occur in the green cover and built-up areas. The built-up areas will replace the green spaces, and more than half a portion of the study area will be transformed into impermeable surfaces by 2050. Similarly, the green surface will reduce to less than half of the study area. So, the figure indicates that the study area will face a massive loss of urban green cover, and it will have to bear urban built-up areas on more than half of its portion by 2050.

The behavior of LULC changes raises various environmental issues, among others. LULC changes are significant concerns in the developing world, where countries experiencing rapid population growth also face a corresponding increase in urban population. The situation becomes more problematic when scholars observe that this trend continues unabated (Adedeji et al. 2020; Hamad et al. 2018; How et al. 2020). Similar trends are evident in Lahore, signaling an alarming situation for future environmental hazards. Therefore, it is imperative to reinvigorate management efforts and take swift measures to ensure the environmental sustainability of the study area.

Similarly, the green areas will decrease to less than half of the study area. Moreover, section C illustrates the net contribution of green spaces in future land cover classification, indicating that the green cover will lose a substantial area (more than 300 km^2) by 2050. Consequently, the figure suggests that the study area will experience a significant loss of urban green cover, with urban built-up areas occupying more than half of its total area by 2050. The expansion of built-up areas leads to a reduction in

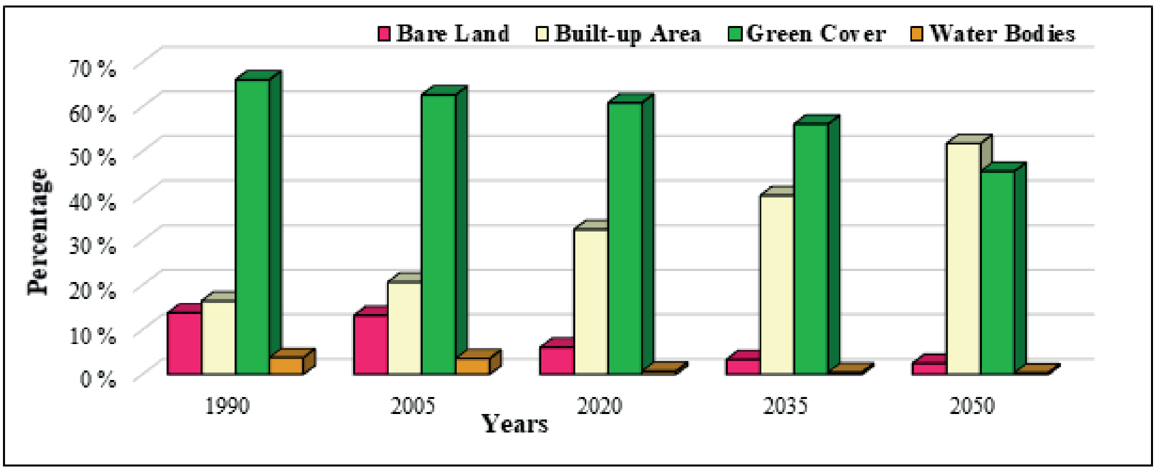

Fig. 11. Land Use Changes in Lahore from 1990 to 2050

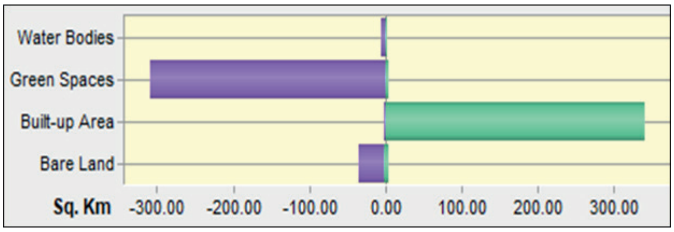

Fig. 12. Land Covers Gain and Loss in Lahore from 2020 to 2050

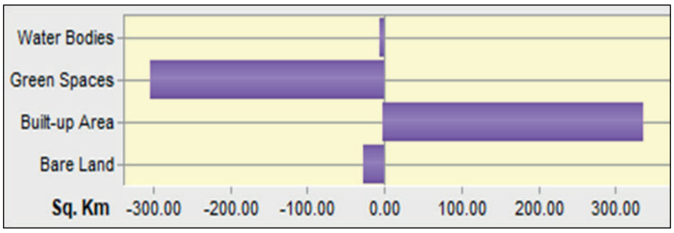

Fig. 13. Net Change within Land Covers in Lahore from 2020 to 2050

agricultural land and the decline of the ecosystem in the area. Increased built-up areas also demand more energy consumption and water resources, contributing to water pollution and urban heat island effects. The rapid increase in the built-up environment is a significant contributor to environmental issues in urban areas (Adedeji et al. 2020; Shao et al. 2021).

The projected LULC classification for 2050 predicts extreme environmental issues in the study area, negatively impacting human well-being (Karimi et al. 2018; Samie et al. 2020). The projection for 2050 indicates that more than half of the study area will be covered by built-up areas, while green cover will occupy less than half of the total land area. The rapid expansion of built-up areas has been observed in various urban settings in the developing world, leading to several environmental issues such as high LST and urban heat island effects, air and water pollution, increased air temperatures, and decreased thermal comfort (Adedeji et al. 2020; Shao et al. 2021).

Observing LST Changes (1990 – 2020)

The LST (Land Surface Temperature) of the study area in 1990, 2005 and 2020 is depicted in Figure 14. The year 1990, shows that the study area had 3.58 km^2 area with the lowest temperature range (8°C – 21°C), 205.48 km^2 with lower temperature (22°C), 515.99 km^2 with low temperatures (23°C), 650.81 km^2 with medium temperatures (24°C), 317 km^2 with high temperatures (25°C), 57.26 km^2 with higher temperatures (26°C), and 9.67 km^2 with highest temperature range (27°C - 32°C). Similarly, in 2005, the LST of the study area encompassed 147.28 km^2 with the lowest temperatures range (8°C – 21°C), 470.64 km^2 with lower temperatures (22°C), 357.92 km^2 with low temperatures (23°C), 239.87 km^2 with medium temperatures (24°C), 352.67 km^2 with high temperatures (25°C), 156.57 km^2 with higher temperatures (26°C) and 35.76 km^2 with highest temperature range (27°C - 32°C) of LST. Likewise, in 2020, the LST of the study area encompassed 118.37 km^2 with the lowest temperatures range (8°C – 21°C), 362.22 km^2 with the lower temperatures (22°C), 341.44 km^2 with low temperatures (23°C), 154.96 km^2 with medium temperatures (24°C), 361.06 km^2 with high temperatures (25°C), 250.24 km^2 with higher temperatures (26°C) and 172.46 km^2 with highest temperature range (27°C - 32°C) of LST.

Relationships between LST and NDVI

Normalized Difference Vegetation Index (NDVI) measures surface reflectance and quantifies vegetation growth and biomass. Therefore, the negative relationships of LST and NDVI authenticate that UGSs caused low LST.

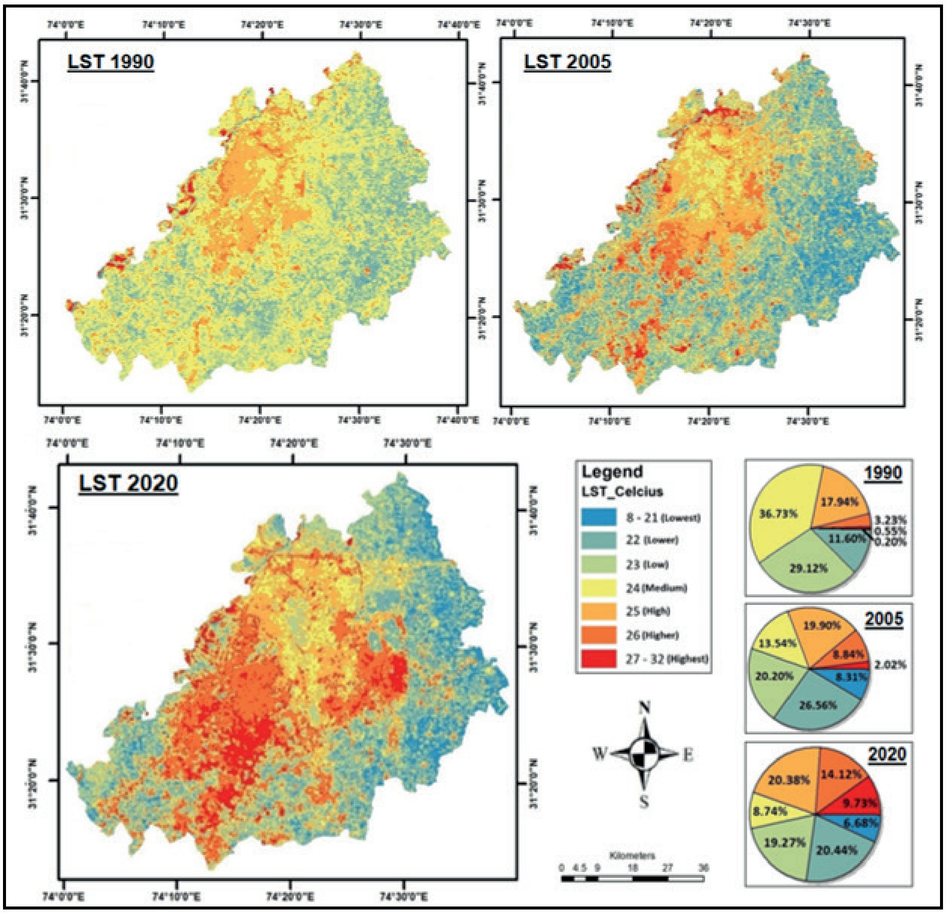

Fig. 14. Land Surface Temperature in Lahore from 1990 to 2020

Figure 15 shows relationships between LST and NDVI in the study area, in which negative relations were found. Moreover, it can be observed that a5.5°C LST decreases from -0.05 to 0.55 NDVI, which indicates that greenness reduces LST.

Relationships between LST and NDBI

Normalized Difference Built-up Index (NDBI) measures surface reflectance and quantifies built-up area and impermeable surface. The mounting of positive NDBI values indicates the increase of built-up and impermeable surfaces (Wu et al., 2016). Relationships between LST and NDBI of the study area are shown in Figure 16, which was found positive. Therefore, it can be assessed that LST 5°C increases from -0.35 to 0.1 NDBI. So, the positive relation between LST and NDBI indicates that the built-up surface increase caused LST and UHI expansion.

Prediction of Land Surface Temperature

An increase in LST is one of the common issues in urban areas caused by the expansion of the built-up structure. Urban expansion alters land into an impermeable surface, the primary cause of rising LST in urban areas, especially in cities that expand and violate environmental rules (Land Surface Temperature - an Overview | ScienceDirect Topics, n.d.; Yan et al. 2020). Similar conditions have been analyzed in the study area in the last 30 years. The study has analyzed the LST of the study area for 1990, 2000, 2010, and 2020. Similarly, the study projected the LST of the study area for 2035 and 2050, which is given below in detail.

The growth of the urban built-up area caused expansion in the impermeable surface. It is a natural phenomenon that the expansion of impermeable surfaces causes the expansion of high LST and urban heat island effects (Uddin & Swapnil 2021). As the study has analyzed, the area under

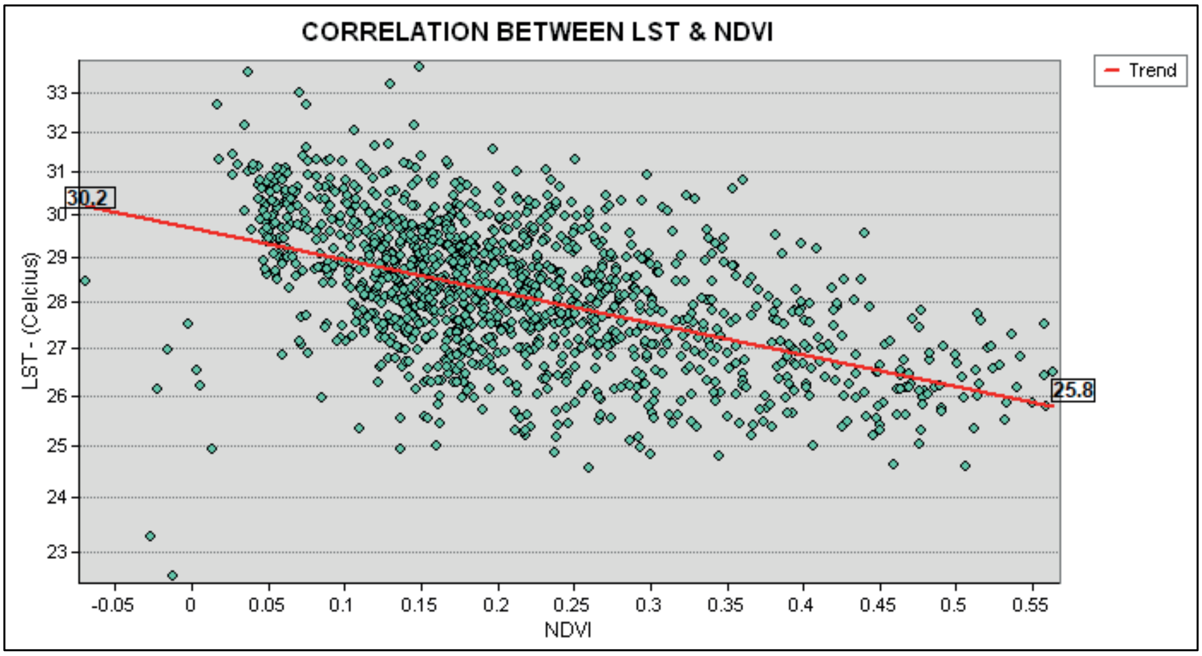

Fig. 15. Relationships between LST and NDVI

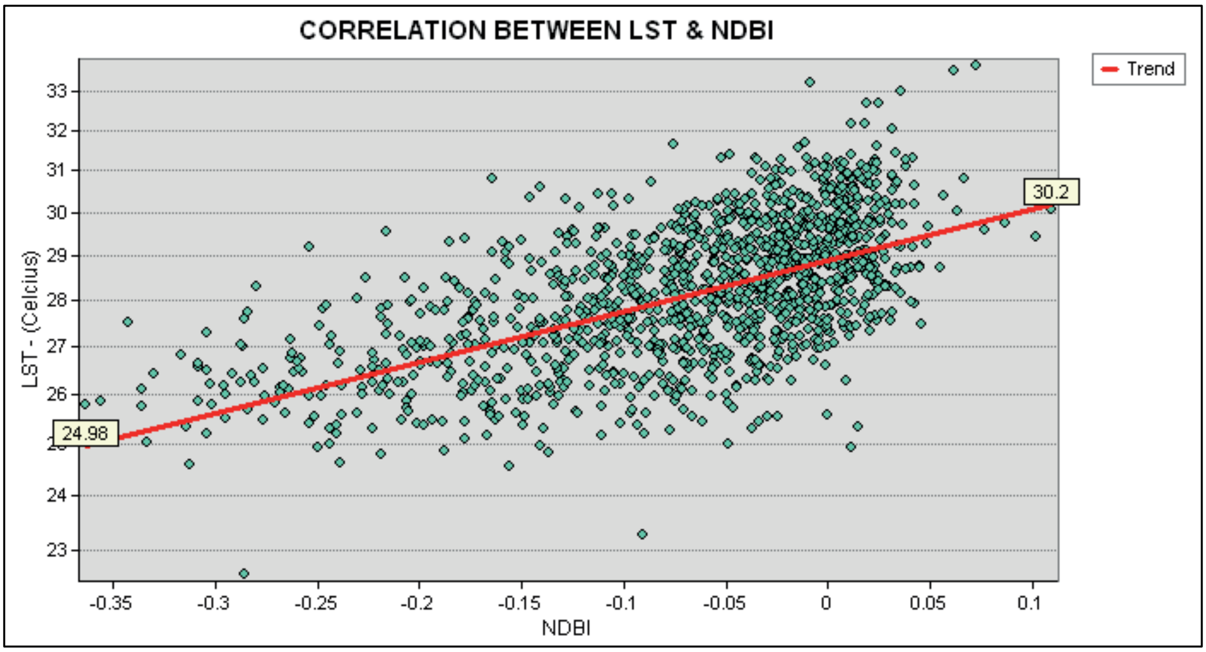

Fig. 16. Relationships Between LST and NDBI

a lower degree of LST decreases with the increase of built-up area, and the area under a higher degree of the land surface increases alternatively. In this way, as demonstrated by the trend over the last three decades, the study generated a projection of LST for 2035 and found that the expansion of the higher range of LST will expand towards the eastern and southern part of the study area as well as more areas will enter from lower degree of LST to higher degree. Therefore, the study projected that the area would face higher LST on projected built-up land, from east to southward. All the details of the LST projection for 2035 can be observed in Figure 17.

Several studies have found that land use changes green surfaces into built-up areas, transforming urban areas into hazardous places. Decreased green covers and expanded built-up land by violating environmental land caused various environmental issues (Tran et al. 2017). The study found a similar situation in Lahore, which is facing several environmental issues. The study analyzed the LST of the study area from 1990 to 2020 and found that the study area faces a continuous expansion in a higher zone of LST. Similarly, the study projected an LST for the study area in 2050 and found that more than half of the study area would enter the high, higher, and highest zones of LST. The areas with lower LST will decrease significantly, and urban heat island effects will expand more. If the same trend of land use changes continues, then it is projected that a higher range of LST will be found over more than 55% of the study area by 2050. A detailed map of projected LST for 2050 can be analyzed in Figure 18 for a more comprehensive understanding. The projected results highlighted that the study area would face higher LST due to the present behavior of land use changes. Therefore, the attention of all responsible authorities and stakeholders is critical to preventing and resolving the expected hazardous conditions in the study area.

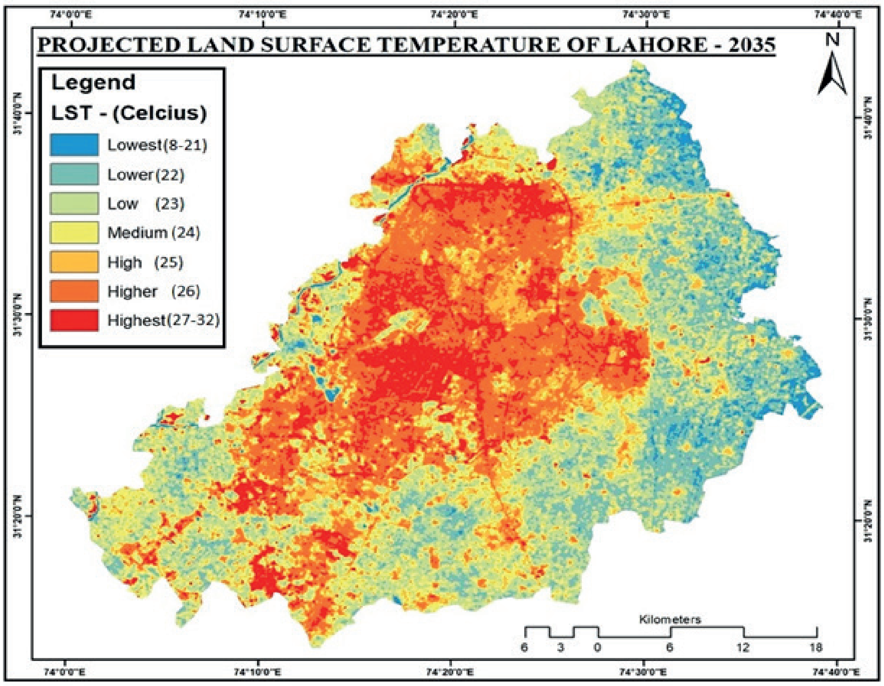

Fig. 17. Projected of Land Surface Temperature in Lahore for 2035

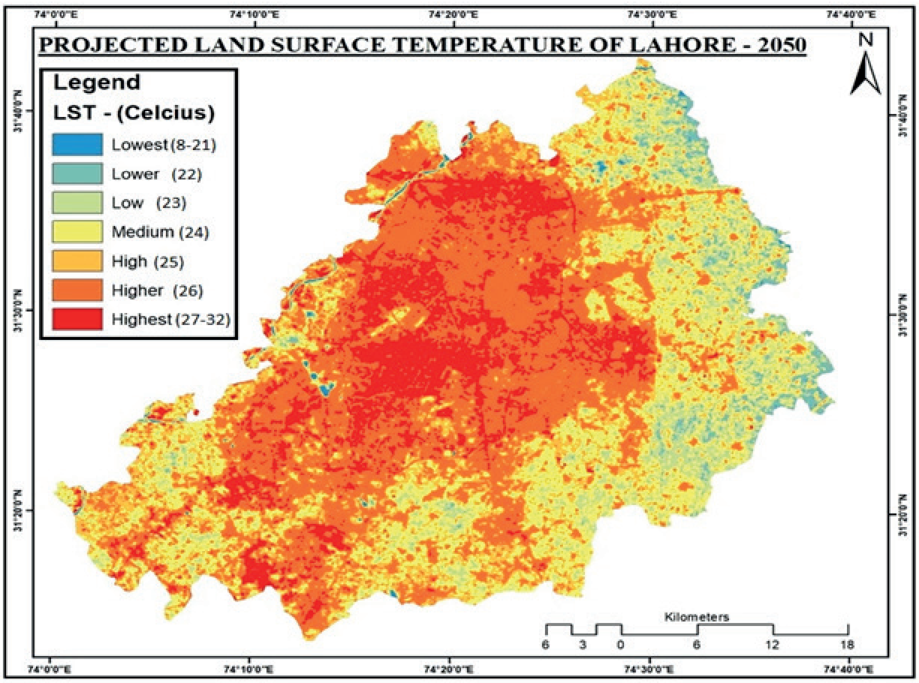

Fig. 18. ojected of Land Surface Temperature in Lahore for 2050

Observed and Predicted LST (1990 – 2020 - 2050)

As the study showed, seven auto-generated (by ArcGIS 10.8) degrees of LST for 2035 and 2050 were ranked as; (i) 8°C - 21°C, (ii) 22°C, (iii) 23°C, (iv) 24°C, (v) 25°C, (vi) 26°C and (vii) 27°C - 32°C. By using these rankings for the LST of the study area, the study did not find any significant change in the lowest (8°C - 21°C) degrees. However, a significant change was found in the shift of 22°C to 23°C LST. The figure shows that the study area had its maximum portion under the 23°C of LST in 1990, which shifted toward the 24°C LST till 2020. Similarly, when the study projected LST for 2035 and 2050, the maximum portion of the study area will be found under the 25°C of LST in 2050. Therefore, the found change indicates that the current LULC changing trend will shift maximum portion of the study area under the High, Higher, and Highest degrees of LST till 2050. The study findings indicate that the study area will push its more than 55% area under the high degree of LST in the next 30 years (till 2050). All the details are given in Figure 19 to understand the readers better.

LST is a crucial variable for climate change and environmental studies (Mundia & James, 2014) and describes the earth's skin temperature, which varies with land use type change. It came from the energy and water balance of the earth's surface (Rozenstein et al. 2014). Several studies have used LST as an essential parameter for monitoring vegetation, global warming, and built-up changes. It is a well-known parameter for environmental issues (Kayet et al. 2016). Lahore (the study area) faces several environmental issues in highly polluted cities worldwide. The analysis demonstrates that the study area is expanding toward the high-temperature zone.

Similarly, a study by Buyadi et al. (2013) on urban expansion found that the expansion of built-up areas was caused by vegetation reduction and microclimatic changes (Buyadi et al. 2013). In recent years, Henao et al. (2020) found that rapid urbanization has considerably replaced green spaces with built-up areas, which has caused environmental problems (Henao et al., 2020). It is analyzed that the most common urban environmental problems are caused by urbanization, like urban thermal discomfort (Feizizadeh et al. 2013). Significant deforestation in Kedah and Perak, located in Malaysia, has reduced forest cover from 39% to 35% in Kedah and from 58% to 49% in Perak. This deforestation caused an increase in LST, whereas areas with vegetation and forest had lower LST (Jaafar et al. 2020). So, the studies demonstrate that reducing or removing green spaces is the leading cause of the increase in LST.

Likewise, the study indicates that the expansion of built-up and barren areas has increased LST. The removal of green spaces has also contributed to higher LST in the study area. Interestingly, adjacent green areas have been observed to exhibit similar LST levels. LST increases with the increase of built-up areas because built-up areas convert permeable land into an impermeable surface, which causes high LST (Ahmed et al. 2013; Tran et al. 2017; How et al. 2020). Therefore, the projected LST of the study area shows that the study area will face the expansion of built-up areas, which will increase the impermeable surface and cause an expansion of the high LST zone. As a result, it is projected that the high, higher, and highest zones of LST will increase in the study area, of which almost half of the study area will be under the influence of high LST. The expansion of high LST can be controlled by providing green spaces within the built-up areas and maintaining existing green spaces because only green spaces are the most suitable and cheapest way to mitigate the expansion of high LST (Rahman et al. 2017; Sun & Chen 2017).

LIMITATIONS

Despite the comprehensive nature of this study on assessing and predicting the impact of land use changes on the thermal environment in Lahore, certain limitations should be acknowledged. First, the reliance on Landsat images from 1990, 2005, and 2020 introduces potential limitations regarding image resolution and temporal frequency, impacting the precision of land use change assessments. Additionally, the predictive modeling for 2050 assumes a linear progression of land use changes, neglecting the impact of potential non-linear trends influenced by unforeseen factors. The study primarily focuses on physical and environmental aspects, overlooking socio-economic factors that intricately contribute to land use changes. The exclusion of detailed analysis of existing and potential future environmental policies and regulations in Lahore limits the understanding of policy dynamics and their impact on mitigating thermal challenges. Furthermore, the single city focus on Lahore

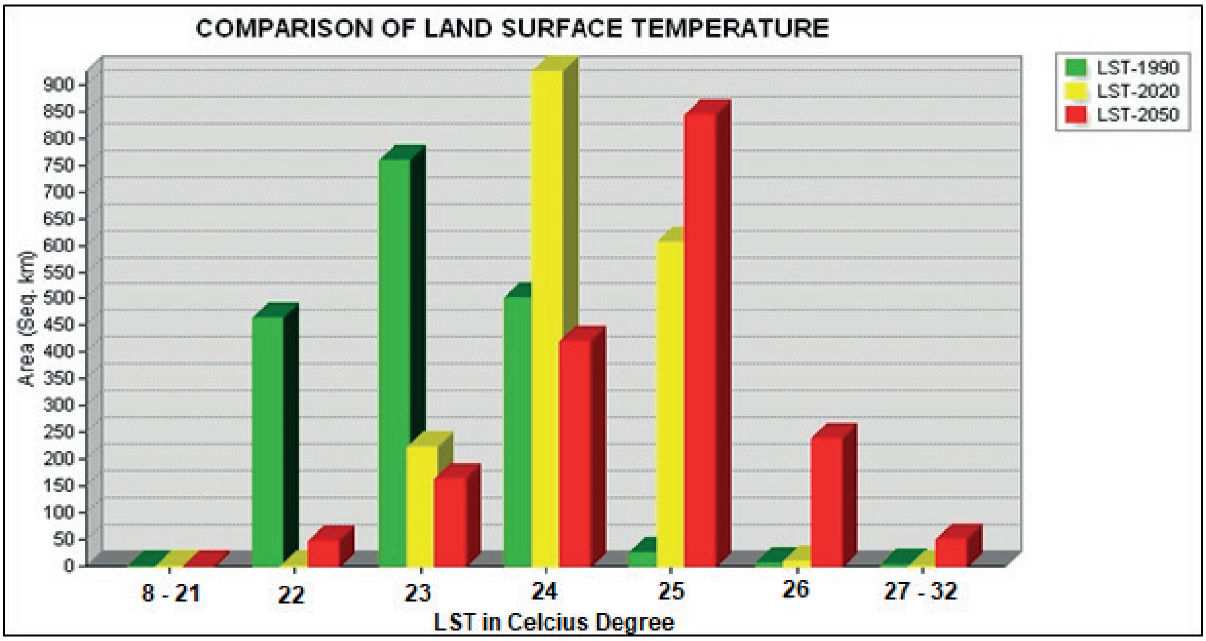

Fig. 19. Predicted Changes in Land Surface Temperature in Lahore from 1990 to 2050

may restrict the universal applicability of findings to other urban contexts, emphasizing the need for caution in extrapolating these results. Finally, uncertainties related to climate change and the simplifications in the land use change modeling process contribute to the limitations of the study, highlighting areas for improvement in future research endeavors.

CONCLUSION

The study area faces rapid land use change and the spread of built-up areas, which is a primary concern of the study. According to the observed land use changes (1990 – 2020), the study area has increased its built-up land cover by almost 100%, pushing its maximum area from the Low to Medium range of LST. Similarly, according to the predicted land use changes (2020 – 2050), the built-up area will spread over more than 50% of the study area by decreasing its green cover by less than 50%. As a result, the maximum area will be found under the High LST range instead of Medium. Therefore, the observed land use changes in Lahore are highly sensitive to its LST, which will affect its urban heat island and other climatic elements because the study area is also found in a country (Pakistan) nominated as one of the top ten impacted by climate change. Therefore, in these circumstances, the increase in a built-up area and LST is highly significant, negatively affecting the environmental sustainability and residents' health. Hence, it is concluded that the study area is threatened by rapid land use changes and its impacts on its LST increase, which demands serious attention and quick action against such activities; otherwise, the study will lose its suitable environment and acceptable homogeneousness of LST. The conservation and expansion of green cover are recommended with increased built-up areas if management aims to maintain the required ecosystem quality for the residents. As demonstrated in the study, urban forest using Miyawaki may be one of the best options to handle the urban thermal environment. Therefore, integrated urban planning that balances built-up areas and green spaces should be promoted. Resources should be allocated for green infrastructure projects, and zoning regulations favoring mixed land use and green area preservation should also be enforced. Furthermore, climate-responsive design practices should be encouraged in conjunction with raising public awareness and fostering community engagement on these issues. Other valuable recommendations include developing green corridors, implementing adaptive land use policies, establishing a robust monitoring system, and encouraging stakeholder collaboration to better inform policy measures. Investing in capacity-building programs for urban planners to better understand and address the complex relationship between land use changes and thermal environments can ultimately address their growing issues. Upon reflecting on the findings of the study and these subsequent recommendations, I realized that such comprehensive measures could ultimately assist in creating a sustainable, resilient, and aesthetically pleasing urban landscape in Lahore, Pakistan. ■

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