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Tracing Lahore's Carbon Sequestration Pathway: Integrating Remote Sensing, GIS and Local Perspective for Urban Ecological Renewal

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Abstract

Unplanned growth of cities is threatening both built and natural systems with long-term consequences. This paper mainly focuses on analyzing the LST, LULC, NDVI and NDBI of Lahore, Pakistan using remote sensing over the past three decades including the impacts of COVID-19 lockdown on the above factors. Urban thermal characteristics were analyzed by investigating the relationships between the land surface temperature (LST), percent impervious surface area, and two indices, the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Built-up Index (NDBI). The objective here is to determine and analyze the spatial variability of LST caused by the land use change between the year 1993 to 2023 in Lahore in the context of urbanization. Further this study integrates the local perspective and their perceptions related to rising temperatures and ecological environment. This study emphasizes on adopting effective strategies, including afforestation, reforestation and urban greening practices (including the creation of carbon sinks) which can significantly improve the CS capacity and reduce climate change and global warming impacts in the fastest-growing cities of developing countries.

Keywords: Carbon Sequestration, Urban Ecology, Thermal Dynamics, NDVI, LST.

1. Introduction

In an era where data-driven solutions are paramount, the blatant data on the global warming crises tell a compelling story and demand our immediate attention (Chen et al., 2006a; Lima et al., 2021; W. Zhang et al., 2014). Concern over global warming has resulted in an international debate and investigation into methods of ameliorating the greenhouse effects and reducing carbon dioxide concentration in the atmosphere (Gratani et al., 2016). The present concentrations of worldwide carbon dioxide emissions, according to the Intergovernmental Panel on Climate Change (IPCC), are substantially greater than those predicted by the most pessimistic forecast (IPCC — Intergovernmental Panel on Climate Change, 2023). While the future of nuclear energy is heavily debated and plagued with ambiguity, renewable energy sources like biomass, wind, and solar are still in early stages and are unable to completely replace the current fossil fuel-based energy sources in the not-too-distant future (Farrelly et al., 2013). The current urgent need for significant CO2 emission reductions could be more affordably met by carbon sequestration solutions (K Murthy, 2013; Kuittinen et al., 2016; Smith, 2016). Carbon sequestration is gaining popularity as an effective strategy to achieve reduced atmospheric carbon targets. Combining knowledge from carbon sequestration studies with the practitioners' experience in making place-specific planting design decisions will be helpful in promoting sustainable carbon sequestration in urban greenspace (Wang et al., 2021). It is a vital approach for minimizing the adverse effects of climate change, which is a serious threat to the entire globe (Abdo & Satyaprakash, 2021).

Cities, being the engines of economic growth having all kind of mechanized activities, are more susceptible to the impacts of climate change (Kuittinen et al., 2016; Zhou et al., 2022). The global urban land area is predicted to triple by 2030 which means that our cities need deep analysis and restructuring (Feinberg, 2023) in order to avoid the undesired circumstances of climate change (Chapman et al., 2020). Developing nations encounter the twofold task of industrialization and striving for advancement, all the while working to reduce CO2 emissions (Avenyo & Tregenna, 2022; Zheng et al., 2022). Consideration should be given to the effect on the potential for plant growth in undeveloped areas, the financial costs associated with the forfeited agricultural potential, and the efficiency of the land-supply chain for various biogenic materials (Farrelly et al., 2013). As noted in the research conducted by (P. Li & Wang, 2021), they assessed the carbon sequestration potential of residential lawns and found that improperly managed lawns, in contrast to bare soil areas, release more CO2 due to ongoing microbial respiration. There is a need to assess the pattern of development in third world countries and it will give the comprehensive picture of current trends and efforts in the wake of mitigating the impacts of climate change (Naikoo et al., 2022). In addition to accessing the patterns of development, there is a need to understand the local perspective in the wake of climate change.

As a methodological approach, this paper conducts an extensive examination of Lahore district's current status, focusing on NDBI, NDVI and LST trends over the last thirty years. It underscores the necessity for efficient natural and urban resource management. In a sprawling mega city like Lahore, with a population exceeding 11.13 million (Aslam et al., 2023), the pressure from this population growth intensifies land use demands, driving deforestation (Yigitcanlar & Dizdaroglu, 2015). This study area's significance lies in addressing these pressing challenges. Additionally, it will highlight specific land areas where ecosystem service tradeoffs and synergies take place within the context of urban expansion and it will provide valuable insights for urban planners, aiding them in making sustainable, environmentally conscious development choices.

Most research on sustainable urban development conducted in past decade suggests that it's essential to understand how much carbon is released and absorbed during urbanization (Cui et al., 2019) and what must be the factors contributing to the varying carbon levels in atmosphere (Rahaman et al., 2022; Z. Zhang et al., 2022). This helps us see how a city is growing and where it's making progress or facing challenges. The primary reasons for the UHI phenomenon are the significant heat generated by urban structures as they absorb and release solar energy and the influence of human-made heat sources (Fadhil et al., 2023). Farrelly et al., 2013 suggested that the future research in this area should focus on using advanced GIS, remote sensing, and machine learning methods as these fields offer several promising approaches for practical applications. Zhang et al., 2009 emphasized on having precise and current data regarding land cover and environmental conditions as it is vital for effective environmental planning.

In numerous past remote sensing studies of urban environments, the NDVI, Normalized NDBI, Urban Heat Island (UHI) and Land Surface Temperature (LST) served as a key indicator for assessing urban climate conditions (Zhang et al., 2009). Vegetation index (VI) is a simple and effective measurement parameter, which is used to indicate the earth surface vegetation covers and crops growth status in remote sensing field (Gandhi et al., 2015). Reductions of temperature via increased vegetation in inner-city green spaces illustrates their relationship with the UHI effect in Lahore using remotely sensed data (Arshad et al., 2022). Tariq & Mumtaz, 2023 used spatio-temporal assessment of multi-spectral remote sensing data for the years 1990, 2004 and 2018 to illustrate how urbanization in Lahore has changed the LST. Lahore city has been facing several environmental issues, but relatively little has been known about the negative impacts of UHI related to urbanization (Nasar-u-Minallah et al., 2023b). Furthermore, this study never fully examined the influence of the city's urban form, such as variations in land use and land cover changes. Several studies focus on the dynamics between LST and NDVI (Anbazhagan S & Paramasivam CR, 2016; Solangi et al., 2019; Weng et al., 2004; Xue et al., 2021) but ignore other important indices that might have better correlation with the surface temperatures. Moreover, in all of this research, the local perspective and their opinions were not taken into account. Additionally, this paper considers the impact of COVID-19 lockdown and how the emissions were impacting all the vegetation cover and its growth during that span. It has also considered the perspective of local people and their opinion is taken regarding the measures needed to be adopted in order to mitigate the impacts of climate change.

2. Materials and Methodology

2.1. Case Study Area and Data Collection

Lahore is the second-largest city in Pakistan in a flat and mostly agricultural region. The population exceeded 11 million in 2017 with an annual growth rate of 4.07% since 1998 as per the census of 2017 (Home | Pakistan Bureau of Statistics, 2023). Lahore is the capital of the Punjab province located at 31°15′ to 31°45′ N and 74°01′ to 74°39′ E (**Figure 1**). It is a semi-arid region that is especially vulnerable to various environmental issues related to the industry, occupational, and transportation pollution (Aslam et al., 2023). The prior CO2 emissions from ODIAC suggest that the Lahore 2014–2019 trend was about 646 kt C/year (an annual 5.9% increase), while the baseline of posterior CO2 emission trend was about 734 kt C/year (an annual 6.7% increase) (Lei et al., 2021). It's a city with high energy consumption and thus an ideal choice for research.

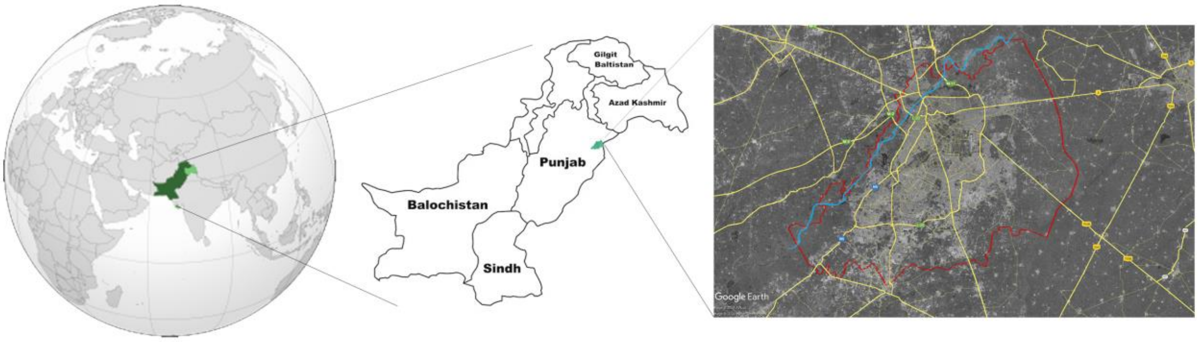

Figure 1: *Case Study Area (Source: authors original work)*

Landsat satellite imageries for March are utilized in this study to portray the spring season and start of summer season to eliminate the effects of cooling and heating. Since this month falls at the beginning of the spring season, the trees' canopy is at its growing period. The imageries of year 1993, 1998, 2003, 2008, 2013, 2018 and 2023 were acquired as presented in ***Table 1***. The images contain multispectral data, and all ten bands were downloaded for the analysis. For the year 1993, imagery from the month of April is taken as it was the only available source.

Table 1: *Data Acquisition*

Landsat	Sensor ID	Date	TIME	Path/Row	Cloud Cover
LANDSAT_5	TM	1993-04-09	04:58:52	149/038	0.00
LANDSAT_5	TM	1998-03-22	05:13:17	149/038	3.00
LANDSAT_7	ETM	2003-03-12	05:25:20	149/038	0.00
LANDSAT_7	ETM	2008-03-25	05:26:44	149/038	0.00
LANDSAT_7	ETM	2013-03-07	05:32:44	149/038	4.00
LANDSAT_8	OLI_TIRS	2018-03-29	05:36:04	149/038	0.00
LANDSAT_8	OLI_TIRS	2023-03-27	05:36:25	149/038	0.01

2.2. Image Pre-processing

All downloaded images were clipped to study area of Lahore district. All Landsat satellite images were subjected to atmospheric, geometric, and radiometric correction. Scan line error for Landsat_7 have been removed for two years, 2008 and 2013. To enhance the accuracy of our calculations, Digital Number (DN) values were converted into ground reflectance through both atmospheric and radiometric corrections. In the methodology employed (Nasar-U-minallah et al., 2021), Thermal Infra-Red Digital Numbers were converted into Top of Atmosphere (TOA) spectral radiance ($L\lambda$) through the application of the formula:

$L\lambda = ML * Qcal + AL – Oi$

with Lλ representing the TOA spectral radiance in Watts/ (m^2 * sr * µm) and ML, Qcal, AL, and Oi being band-specific factors integral to precise radiance conversion. These factors, unique to each band, were incorporated into the formula. Subsequently, the spectral radiance data underwent transformation into Top of Atmosphere wavelength brightness Temperature (BT) expressed in degrees Celsius. This was done using the formula.

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

where BT signifies the top of atmosphere BT, and K1 and K2 are constants specific to Band. The inclusion of precise values for these constants corresponding to the bands used in the analysis are important for precise temperature calculations.

2.3. Derivation of LST, NDVI, and NDBI

The National Aeronautics and Space Administration of USA (NASA) uses 7-band data for feature extraction (Gandhi et al., 2015). The stacked layers were then used to analyze the land use patterns of the district. All the formulae adopted below were used in numerous studies and the accuracy estimation was satisfactory (Bherwani et al., 2022; Nasar-u-Minallah et al., 2023; Subzar Malik et al., 2019). In our research, NDVI is opted to characterize and explore alterations in urban greenery between 1993 and 2023. The aim was to identify the vegetation cover of Lahore District over the course of a decade. Numerous indices are available to identify areas with vegetation in remote sensing images. One commonly used and widely recognized index is NDVI, which holds significance in global environmental and climate change research. NDVI is computed as the contrast in reflectance between the red and near-infrared bands of the canopy (Gandhi et al., 2015). These two bands, containing over 90% of vegetation information, are ubiquitous in earth observation satellites (S. Li et al., 2021).

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

This step is crucial for understanding variations in vegetation cover. Subsequently, Land Surface Emissivity (E) was determined, primarily relying on the proportion of vegetation (PV and emissivity (E) was derived as $E = 0.004 * PV + 0.986$. The next step involved the computation of LST using BT, wavelength of emitted radiance (λ), and E. The formula for LST is

$$LST = BT / (1 + (\lambda * BT / c2) * \ln(E))$$

with λ being the wavelength of emitted radiance and c2 as a constant value for the wavelength (in mK) as frequently seen in literature (Nasar-u-Minallah et al., 2023). The NDBI has been specifically designed for the detection and mapping of urban and built-up areas (Zhang et al., 2009).

$$NDBI = (SWIR\ 1 - NIR)/ (SWIR\ 1 + NIR)$$

2.4. Local Perspective

The study involved collecting responses from 205 participants in Lahore through a structured questionnaire. The survey focused on individuals across various age groups, educational backgrounds, occupations, and income levels. The questionnaire comprised 25 questions, primarily addressing respondents' awareness of climate change, concerns about local impacts, and perceptions regarding the decline of green spaces in Lahore. Demographic information such as age, gender, education, occupation, and income was obtained for categorization. Noteworthy is the predominant representation of individuals aged 17-25 (66.4%) and those holding a Bachelor's degree (66.3%). The questionnaire encompassed sections on understanding climate change, identifying causes of greenery decline, evaluating government initiatives, and assessing individual willingness to adopt eco-friendly practices. The study aimed to gain insights into the awareness, concerns, and perceptions of Lahore residents regarding climate change and ecological renewal.

3. Analysis and Findings

The findings provide a look at urban growth, environmental shifts, and how Lahore is adapting to these changes. **Figure 2** provides an overview of land cover dynamics. The land cover types include Barren, Built-up, Vegetation, and Water Bodies. Over the course of three decades from 1993 to 2023, the land cover has undergone significant changes. Barren land has seen fluctuations, with a notable increase in 2008 followed by a significant decrease in 2023. It is due to the rapid mobilization of people from inner city areas to the suburbs. Built-up areas have seen consistent growth, particularly evident in 2003 and 2018, suggesting increased urbanization and the invasion of city into the adjacent agricultural lands.

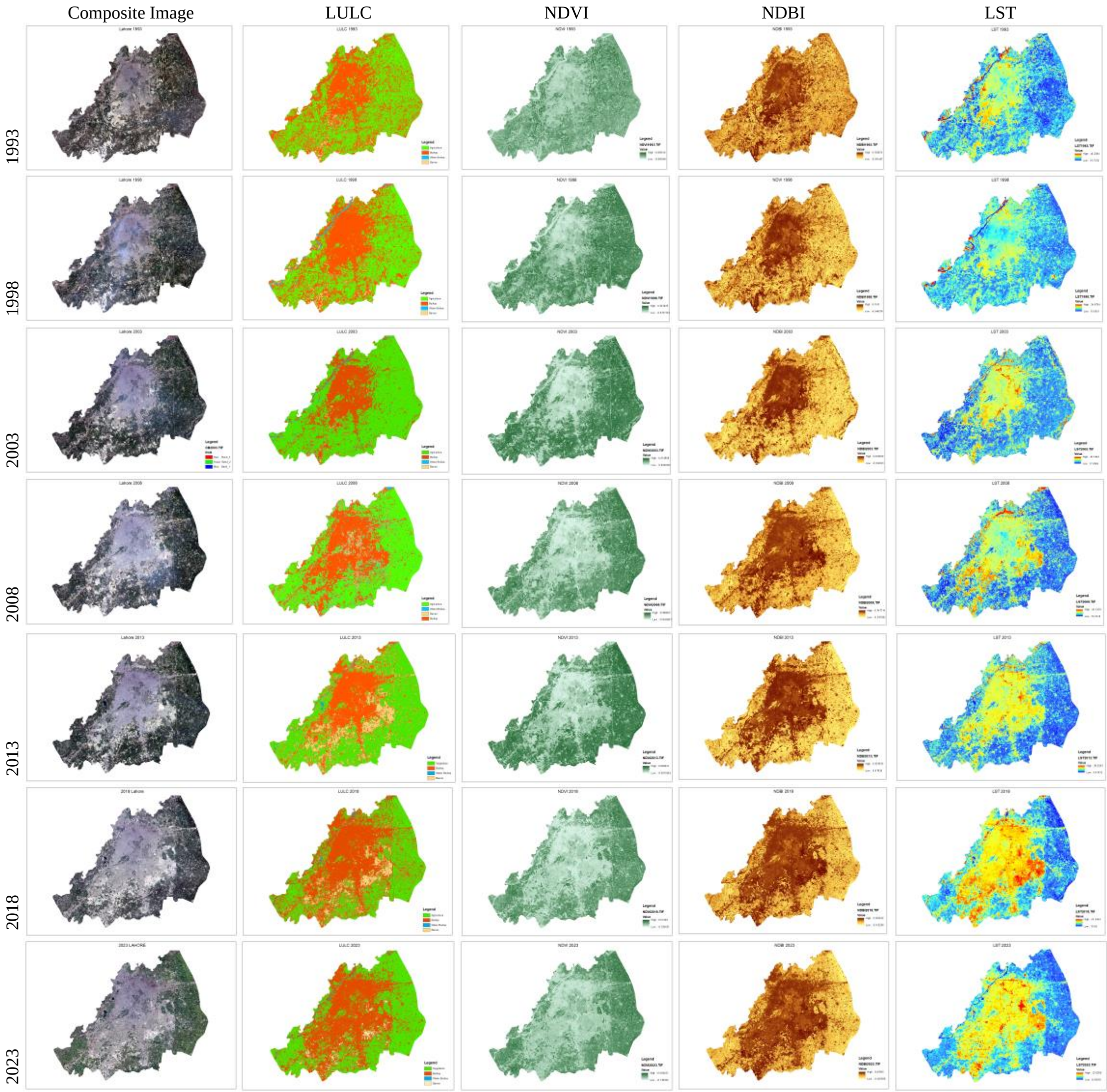

Figure 2: *LULC, NDVI, NDBI (1993-2023 (Source: authors original work)*

Vegetation cover, while fluctuating, has maintained a declining trend over the years. As the city is expanding, the green lands of the districts are declining. Water bodies show a consistent but minor decline and it's due to the desperate state of River Ravi. This water reservoir can be used as a carbon sink considering its carbon capture ability. Once integrated with green furniture, this river can be turned into a source of cooling and will help with the declining water table levels of Lahore. The LST data provided above displays an overall trend from 1993 to 2023. High temperature values have notably increased from 17.44°C in 1993 to 33.65°C in 2023 within the district boundary. The degraded barren land around Ravi River is contributing more to the increased temperatures in the district as displayed in the image, thus indicating the need for prompt management. Factors contributing to this could include urbanization and climate change. Such an increase can have adverse effects on the environment and human health, including a higher risk of heat-related illnesses and these factors were also highly suggested by the local respondents. In the context of COVID-19, it's important to note that after 2021, there was a drop in LST, possibly due to reduced economic activities and mobility during lockdowns. The relationship between NDVI, NDBI and LST suggests that increases in NDVI contributes to a lower LST values (**Figure 3**). Similarly, NDBI, reflecting built-up areas, showed a stronger positive relationship with the LST (**Figure 4**).

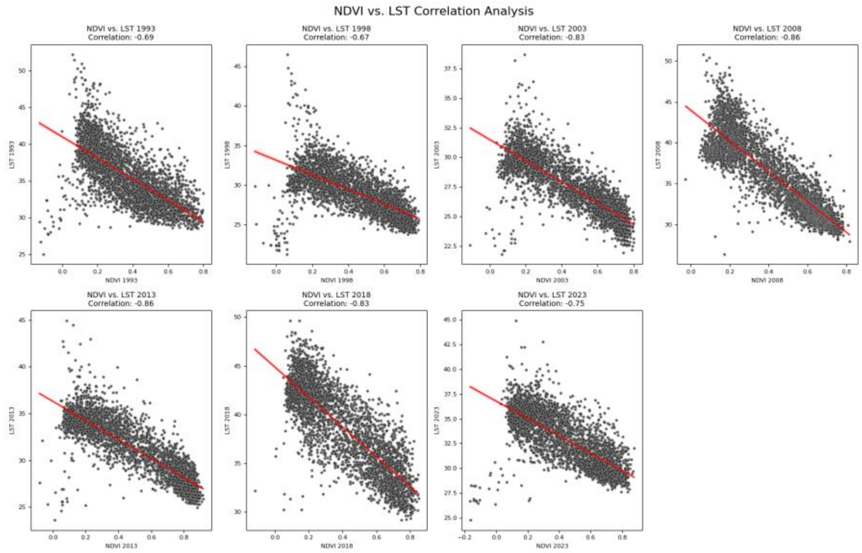

Figure 3: *NDVI vs. LST Correlation Analysis*

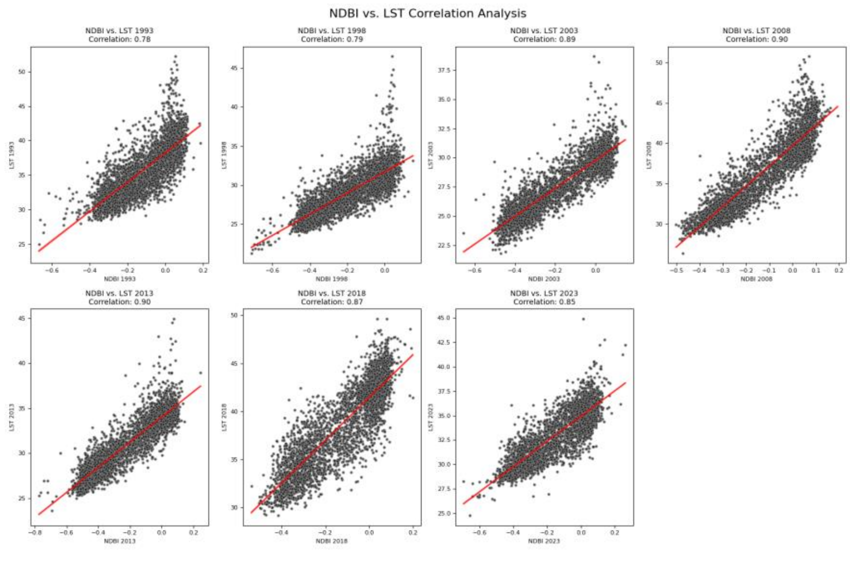

Figure 4*: NDBI vs. LST Correlation Analysis*

NDBI steadily increased over the years as the city grows more congested over the year and a drastic change is seen over the decades. The relationship between NDBI and LST suggests that increased urbanization is contributing to higher temperatures. The high NDVI ranging from 0.5 to 0.65 is seen outside the Lahore boundary towards the east, northeast and southeast due to the presence of agricultural land towards the Indian border and adjoining areas. The NDVI in the central region of Lahore ranges from 0.2 to 0.3 because of the rapid increase in population and emissions from anthropogenic sources. The low values of NDVI are due to the dense human settlements and fewer green spaces (Rana et al., 2023). It's well-established that the correlation between NDVI and LST is nonlinear (Fatemi & Narangifard, 2019; Gorgani et al., n.d.; Weng et al., 2004; Wetherley et al., 2018), mainly because areas with mostly exposed ground surfaces tend to display greater variations in surface temperature compared to densely vegetated regions (Zhang et al., 2009). The NDVI data shows fluctuations in vegetation. With the increased amount of CO_2 in atmosphere, the vegetation health improved to some extent and thus resulted in increased NDVI. All the previous studies conducted to analyze the relationship between NDVI and LST (Alademomi et al., 2022; Chen et al., 2006b; Mathew et al., 2017; Zhang et al., 2009) shows that both share a negative correlation and it is observed in the analysis (**Figure 5**).

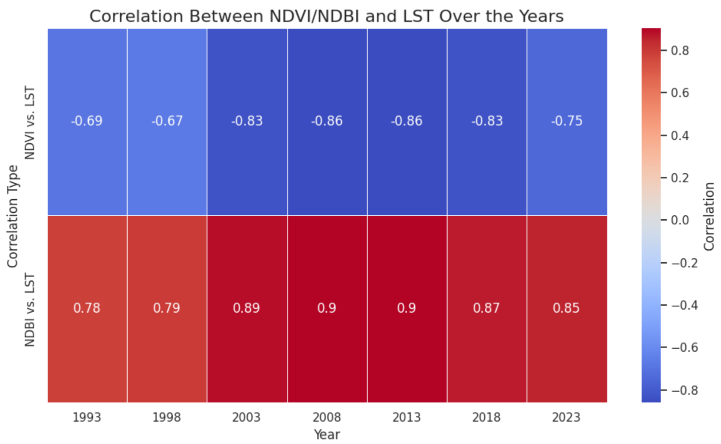

***Figure 5**: Correlation Analysis: NDVI & NDBI vs. LST (1993–2023)*

From the analysis of local perspective, it was seen that a significant portion of the respondents demonstrated a commendable level of familiarity with the topic, with 43.10% claimed to be quite familiar, very familiar, or extremely familiar. Additionally, the acknowledgment of changing climatic conditions is notably high, with 67.80% expressing familiarity at higher levels. Almost 89.20% of respondents observed changes in local weather patterns, indicating the community's increased environmental awareness. Concerns about climate change impacts are prevalent, as 81.90% of respondents indicated varying degrees of concern, with 23.10% expressing deep concern. Moreover, an overwhelming 93.30% recognize the impact of vegetation on local temperatures, suggesting a strong understanding of the ecological role of green parks and urban green spaces. The majority (83.10%) also observed a decrease in green infrastructure, indicating a perceptible change in the city's environmental fabric and its reflecting the findings from land use land cover change observed.

While assessing the contribution of human activities to vegetation decline, a diverse range of opinions were seen, with 49.80% acknowledging moderate to high contributions. Concerns about the future of Lahore are significant, with 74.40% expressing worries about a worsening situation. The identified factors contributing to the rise in temperature highlight key environmental challenges, with pollution, deforestation, and vehicular traffic being major concerns. From the local perspective, anticipated future issues include rapid urbanization, carbon emissions, and inadequate government control, collectively reflecting the future trajectory of the city. Respondents link vegetation decline to a range of negative impacts on life quality, emphasizing concerns such as respiratory diseases, pollution, and degraded environments. The perceived consequences of vegetation decline align with global environmental issues, with a predominant focus on global warming, smog, and the city becoming inhospitable.

The responses indicate a clear lack of awareness among locals regarding government initiatives on climate change, with 50.80% expressing unawareness. Among those aware, satisfaction levels vary, with 45.60% expressing dissatisfaction. A strong motivation for promoting greenery among the people is observed. In terms of lifestyle changes, a majority (69.70%) are willing to make adjustments, indicating a significant openness to adopting eco-friendly practices. Encouragingly, 83.60% are involved in motivating others to protect vegetation. Regarding measures needed to prevent vegetation decline, respondents emphasized on the conservation of urban forests, and government initiatives with strict laws and policies. People are willing to contribute through diverse means, including home plantation (34.2%), public awareness campaigns (11.6%), and reduced consumption of wood products (4.5%). These findings underscore a high level of individual commitment and willingness to contribute towards environmental conservation efforts.

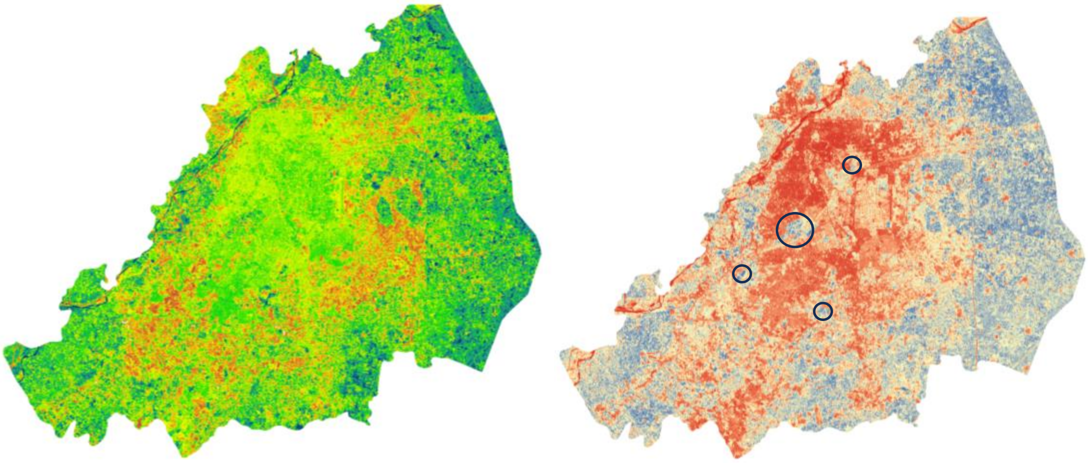

Figure 6: *Land Converted to Built-up Area (Left), Potential Locations for Carbon Sink within Lahore (Right)*

From 1993 to 2023, there has been a gradual conversion of land into built-up areas, as illustrated in red in **Figure 6** (left). Conversely, the imagery on the right highlights the green spaces within the city that have been preserved over the past three decades. These urban green areas possess significant potential to function as carbon sinks.

4. Conclusion and Recommendation

The above analysis specifies potential sites and areas where significant transformations can be made. The barren land can be converted into useful carbon sink if developed properly. As the city will continue to expand, the situation will only get worse. Environmental challenges related to green spaces, limited vegetation, and urban expansion are separate concerns from those associated with energy consumption and carbon emissions and addressing these issues requires different approaches and solutions. (Ali et al., 2018). Numerous cities are formulating strategies to encourage the proliferation of green spaces as an initiative to decrease their overall net greenhouse gas emissions (Velasco et al., 2016). As an important Nature-based solution measure in mitigating rising temperatures and reducing carbon emissions, the use of green infrastructure has grown in popularity (Xi et al., 2022). To foster urban environmental management, last decades have seen numerous heat mitigation strategies been proposed, including the use of innovative building and pavement materials, urban green (vegetation) or blue (water) infrastructure and design of urban morphology (P. Li & Wang, 2021) and such strategies varies in local context.

This process of integrating green infrastructure with our urban concrete structures, is actually the phenomenon of sequestering carbon and it further includes urban framing, vertical gardening, rooftops and well-maintained urban parks. Vegetated water sensitive urban design (WSUD) technologies, reforestation, afforestation, and soil carbon sequestration are examples of natural solutions that have proved effective in reducing greenhouse gas emissions (P. Li & Wang, 2021). Future research should focus on encouraging public participation in the design of sustainable carbon sinks in urban public green spaces while enhancing the precision of measurements (Zhao et al., 2023). Layers of natural biomass will act as an insulating material in an urban setting and can drastically minimize the UHI phenomenon (Farrelly et al., 2013). Growing space and planting potential could be increased by locating parking lots and above-ground utility lines below ground (Jo, 2002). Tree species that have high growth rates, even under adverse urban growing conditions, should be planted. It goes without saying that disturbing natural lands will release the carbon stored in vegetation and soils back to the atmosphere (Jo, 2002). Since roofs represent 21-26% of urban areas, they provide a unique opportunity to utilize these typically unused spaces to address pollution (Rowe, 2011). It is important to expand decarbonization scenarios to accelerate net-zero carbon cities (Dong & He, 2023). Urban rooftops are trending and will be effective in neutralizing the temperatures within cities as building rooftop occupies 20–50% of urban surfaces (Dong & He, 2023). The cooling efficiency is highest where the wind direction is parallel to the belt greens and trees with large canopies (Xi et al., 2022). Additionally, complex plant communities can bring more ecological benefits to urban environments than single-plant communities (Zhao et al., 2023).

Environmental taxes or subsidies that support the adoption of green construction materials could advance a change towards a greener building sector (Farrelly et al., 2013) as the people as mostly looking up toward government for the strict enforcement of laws. Reduce greenhouse gas emissions by providing less auto dependent development, and ease the pressure on environmentally sensitive areas by preventing urban sprawl as well as restoring park and greenway systems. A vision serves as a guiding framework for future decision-making and gives communities a chance to rebuild their cities in a sustainable direction (Yigitcanlar & Dizdaroglu, 2015).

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