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Impact of Urban Vegetation Loss on Urban Heat Islands: A Case Study of Chennai Metropolitan Area

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Abstract

Urban vegetation and green cover provide the urban environments with many ecosystem services and are effective in mitigating the Urban Heat Island (UHI) effect. UHIs are formed in areas with increased Land Surface Temperatures (LST) and have various negative impacts on the thermal environment. **Objective**: This study aims to analyse how the urban vegetation and green cover play a key role in decreasing the LST in a selected city i.e., Chennai Metropolitan Area (CMA) and develop strategies for the mitigation of UHI. **Methods:** The relationship between the LST and urban vegetation cover is analysed for the CMA. The study applies remote sensing and LANDSAT 8 data to study the Normalized Difference Vegetation Index (NDVI), LST and green cover loss for the summer months of 2013 and 2022. **Findings:** Change detection of NDVI and LST in CMA shows a decrease of green cover by 13.33% and an increase of LST by 6.53°C between 2013 and 2022. The study reveals a weak UHI effect in regions with vegetation and a substantial negative association between the LST and NDVI. The study findings show a reduced quality of green cover in CMA which requires further attention. **Novelty:** This study covers the assessment of vegetation loss and its impact on LST in the recent decade bridging the gap in the studies in the extended metropolitan region of Chennai. Strategies that can be incorporated in the urban and landscape design and planning process to improve the urban vegetation of CMA are indicated in the study.

Keywords: Urban Vegetation; Urban Heat Island; Green Cover; Change Detection; UHI Mitigation Strategies

1 Introduction

Urban regions are the most dynamically altered landscapes on earth. The extent of urban land has rapidly increased over the recent decades and metropolitan areas are expected to continue to grow. As the built environment gradually replaces natural cover, it causes a warming effect affecting the urban thermal environment and the urban ecosystems.

Cities experiencing warmer temperatures than the neighbouring rural areas is known as UHI. The ability of the surfaces in each environment to absorb and hold heat is what determines the temperature differential between metropolitan and less developed rural locations. Urban surfaces like roads and rooftops, which absorb and emit heat more intensely than natural surfaces, are the major cause of the UHI effect. The UHI effect has an impact on communities by raising the daily mean air temperature [(1)]. This causes environmental pollution, heat-related disease, and mortality, and amplifies regional climate change [(1)].

There are two types of heat islands based on the way they are formed. Urban surfaces like roads and rooftops, which absorb and emit heat more intensely than natural surfaces, account for surface heat islands. The second type of UHI, atmospheric heat islands have warmer air in urban regions than in rural regions. In comparison to the surface heat islands, the intensity of atmospheric heat islands is lower, and due to the delayed release of heat from urban infrastructure, atmospheric urban heat islands are frequently low in the late morning and throughout the day, becoming more prominent after nightfall. The techniques used to identify and measure the impacts, and methods available to cool the two types of Urban heat islands, differ significantly. Numerous techniques, including field observations, remote sensing, and numerical modeling, can be used to conduct UHI studies. Cutting-edge computer technology and satellite imagery with high temporal and spatial resolution are now effective tools to measure UHIs in greater detail [(2)]. Land Surface Temperatures (LST) are thought to be a valid measure of the UHI since they closely match near-surface temperatures [(3)]. Thus, LST maps are used to calculate the surface Urban Heat Island effect in the UHI studies.

Urban greenery can contribute to the regulation of urban microclimates, the reduction of flood risk, and the promotion of biodiversity, besides providing recreational opportunities. These advantages are usually referred to as "urban ecosystem services". Urban vegetation offers a variety of ecological services that can enhance public health, increase comfort for residents, and have significant economic benefits [(4)]. However, areas of natural and semi-natural vegetation in and around cities are frequently developed during the urbanisation process to sustain the population and economic expansion, which have resulted in a decline in the amount of greenery in many cities [(4)]. To quantify the vegetation in an area, Normalized Difference Vegetation Index (NDVI), a metric derived from remote-sensing satellite data, is widely used. NDVI serves as a reliable marker for monitoring variations in vegetation cover brought on by human activity.

The nature and strength of the relationship between LST and NDVI have been the focus of research on UHI. Analysis of Beijing's urban heat island by Yao et al., [(5)] has confirmed that there is a linear relationship between UHI and urban vegetation. Urban thermal environments are affected by the landscape composition as well as the spatial configuration of green spaces in cities. A study on urban vegetation configuration and LST in Changchun, China by Zhibin et al., established a negative correlation between LST and Green cover [(6)]. A 10% increase in the green cover decreased the LST between 0.81 °C to 1.17 °C depending on the size of the open space [(6)]. A negative correlation was found between LST and NDVI as well. Further, the study established the relationship between the quality of vegetation and LST by finding that the LST decreased by 2.53 °C to 3.62 °C with a 0.1 increase in NDVI value [(6)].

UHI studies have been carried out in many cities of tropical and continental climates with the scale of the study areas ranging from City scale to City-block scale. However, there is a dearth of urban climate behaviour studies of South Asian cities using remotely sensed images [(7)]. Moreover, as cities grow, their boundaries are expanded to accommodate the new growth for better long-term planning and these extended boundaries shape the urban environment. As the relationship between UHI and NDVI differs due to the geophysical, climatic and urban growth characteristics [(7)], understanding UHI in the extended city is vital for planning and developing mitigation strategies. Thus, this paper aims to analyse the relationship between LST and NDVI in the city of Chennai, Tamil Nadu, India in the past decade i.e., in 2013 and 2022, setting the study area as the CMA extending over 1189 km^2. The majority of UHI research on Chennai to date has focused on the Greater Chennai Corporation (GCC) covering an area of 426 km^2 Research focusing on the expanded boundary of the CMA is rarely reported in the past decade. Moreover, published UHI studies on Chennai have analysed the LST till the year 2017 using remotely sensed images of 2017. Thus, this study contributes by using the most recent satellite data i.e., LANDSAT 8 images of 2022 and analysing the UHI effect in the extended metropolitan region of Chennai. The article also stresses the need for mitigation strategies that would be effective in reducing the UHI in the study area by improving the urban vegetation.

2 Methodology

2.1 Study Area

The CMA, which represents the hot and humid tropical climate, is located between 12° 50 '49" N and 13° 17' 24"N latitude and 79° 59 '53" E and 80° 20' 12"E longitude along the south-eastern coast of India. It is situated on a coastal plain, 6 meters above sea level on average. The location and the boundary of the study area are marked in Figure 1. The CMA is made up of GCC, Avadi Corporation, Tambaram Corporation, 5 Municipalities and 3 Town Panchayats and 10 Panchayat Unions comprising

179 villages. GCC, which is part of CMA, extends over an area of 426 square kilometers and has been the focus of most UHI studies to date. The CMA's urban population is close to 8.6 million, and its total area is 1189 sq. km. Due to the CMA's significant industrialization and rapid growth, its population has increased significantly over the previous 20 years [8]. Thus, CMA is selected as the study area to analyse the relationship between urban vegetation and land surface temperature in 2013 and 2022.

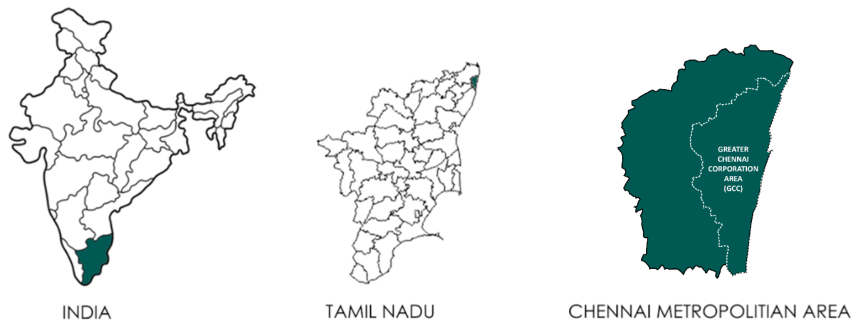

Fig 1. Location and boundary of study area – Chennai Metropolitan Area

2.2 Data set

For the Chennai metropolitan area, the study employed the use of band 4, band 5 and band 10 of Landsat 8 satellite images with a resolution of 30, 30, and 100 m and wavelengths of 0.64-0.67, 0.85-0.88 and 10.6-11.19 micrometers, respectively. The Landsat images having less than 15% cloud cover for the summers of 2013 and 2022 were acquired from the USGS Website.

2.3 Methodology

UHI studies have used the Geographical Information System (GIS) to generate and analyse the NDVI and LST data. Recent studies in the past decade have generated the NDVI and LST maps of cities using cloud-free LANDSAT 8 satellite imagery. The LST and NDVI for the years 2013 and 2022 for the CMA are estimated using the Landsat 8 thermal bands. The LST and NDVI were calculated using the raster calculator tool in QGIS v3.28. The LST data is analysed to identify the heat islands and cool pockets for the years 2013 and 2022. The NDVI data is re-classified as waterbody, non-vegetated areas and vegetated areas. Through visual observation, the relationship between NDVI and LST is observed to find how areas with higher vegetation have lower land surface temperatures. Further, the temporal change in the NDVI is also calculated between 2013 and 2022 to detect the change and loss in urban vegetation.

2.3.1 Mapping LST and NDVI

Normalized Difference Vegetation Index (NDVI) is the basic vegetation index that is a reliable indicator to track changes in vegetation coverage induced by human activities like building or by natural occurrences like drought, was developed to analyse the quantitative distribution of vegetation cover and its density. The NDVI values are derived by the formula as given below.

NDVI = (NIR – RED) / (NIR + RED)

Where Band 5 for Landsat-8 Operation Land Imager (OLI) and Band 4 for Landsat-5 Thematic Mapper I respectively represent NIR. The value range of the NDVI is -1 to 1. According to the NASA Earth Observatory for measuring vegetation, Negative values of NDVI (values approaching -1) correspond to water. Values close to zero (-0.1 to 0.1) generally correspond to barren areas of rock, sand, or snow. Low, positive values represent shrub and grassland (approximately 0.2 to 0.4), while high values indicate good vegetation with temperate and tropical rainforests (values approaching 1). In this study, the NDVI values were re-classified as poor vegetation (NDVI values between 0.2-0.3), Moderate vegetation (NDVI values between 0.3-0.4) and good vegetation (with NDVI values above 0.4). The change detection of NDVI between 2013 and 2022 would reveal the areas in the study area with maximum loss in vegetation.

Land Surface Temperature (LST) calculations are done with a series of raster calculations using Band 10 and 11 of LANDSAT 8 satellite images. The LANDSAT 8 Collection 1 input image is used to derive the top of atmospheric spectral radiance, brightness temperature conversion, proportion of vegetation and emissivity to calculate the LST of the study area.

The raster calculations used to calculate NDVI and LST in QGIS v3.28 are shown in the flowchart in Figure 2.

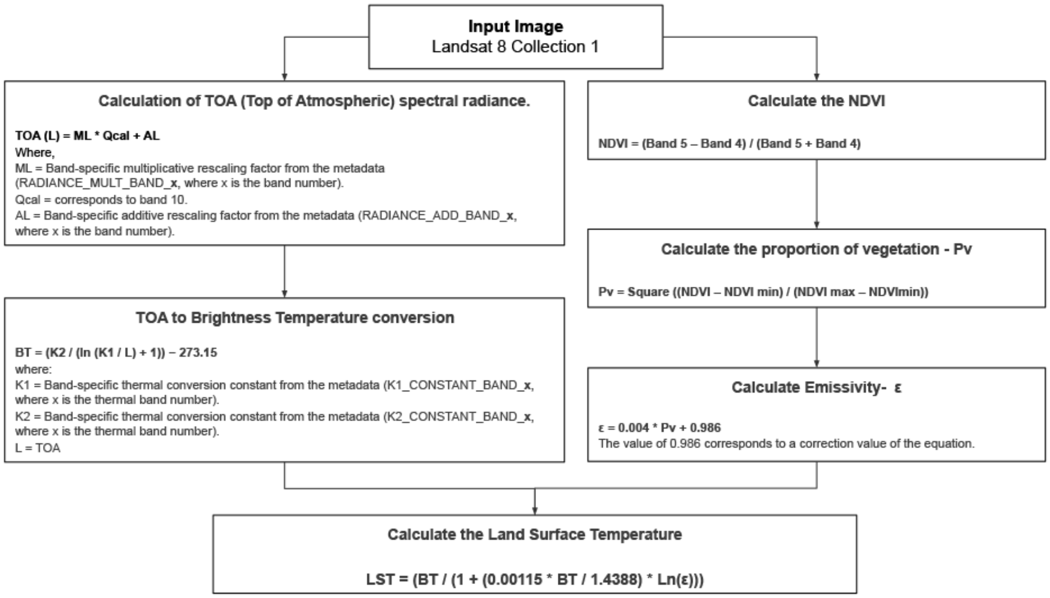

Fig 2. Flowchart of raster calculations to derive NDVI and LST in QGIS

2.3.2 Change detection mapping

To understand the temporal loss in vegetation from 2013-2022, change detection of NDVI is mapped using the SCP plugin in QGIS. The method calculates the changes observed in the NDVI of both years and the pixels which have undergone a change from vegetation to non-vegetated areas are highlighted to show the loss in vegetation. This is done to observe the regions within CMA with a drastic loss in vegetation due to the rapid urbanisation that has occurred.

2.3.3 Validation

To check the accuracy of the maps generated in QGIS, the NDVI maps were validated with On-screen visual verification from Google Earth imagery. Digital numbers of the Operational Land Imager (OLI) images of Landsat- 8 were refined to radiance measurements by using the US Geological Survey coefficients, top-of-atmosphere calculations and brightness temperature conversions as accuracy corrections.

3 Results and Discussion

The change in vegetation characteristics and land surface temperatures detected in this study are presented below.

3.1 Loss in Vegetation (2013-2022)

The change in quantity and quality of vegetation in CMA is analysed as shown in Figure 3. The loss in vegetation cover between 2013 and 2022 in the CMA is 158.54 sq. km which is 13.33% of the total CMA area. The vegetation loss is observed to be prominent in the northern part and in the central to Southern parts of CMA where there is rapid urbanisation and Land use and land cover changes. The minimum and maximum NDVI in the study area observed for the year 2013 is -0.11 and 0.49 and it is found to have declined to -0.12 and 0.46 for the year 2022 (as shown in Figure 4 a and Figure 5 a). On the contrary, the study by M. Faizan comparing the NDVI from 2000 to 2020 for the Greater Chennai Corporation (City area) shows an overall rise in vegetation patterns (Values NDVI)[9] and attributes the rise in vegetation to greening programs and strategies in Chennai corporation area. However, the results of this study show a declining trend in vegetation pattern in the growing CMA and highlights the need for immediate policies and strategies to increase the urban vegetation for reducing the effects of urban heat island effect in the CMA.

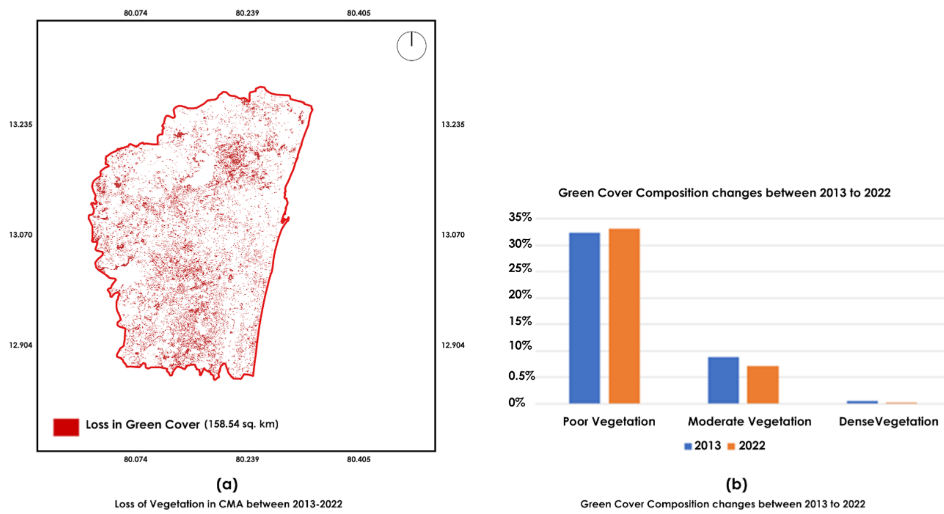

Fig 3. a) Loss of Vegetation in CMA between 2013-2022. b) Green Cover Composition changes between 2013 to 2022

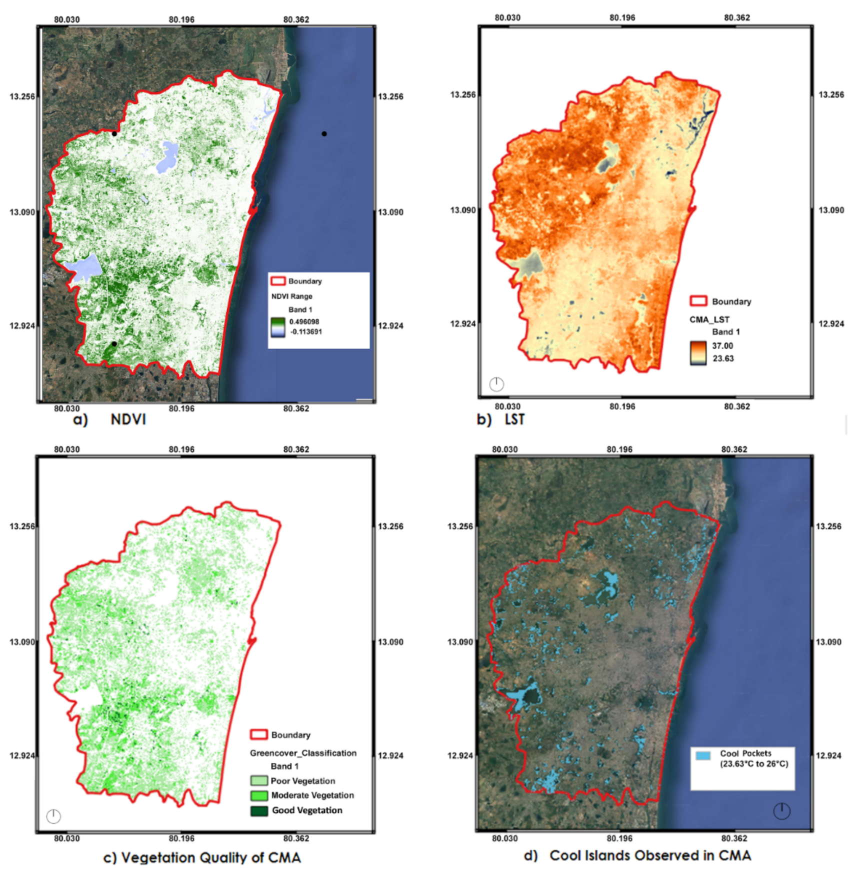

Fig 4. Map of CMA of June 2013, showing a) NDVI b) LST c) Vegetation Quality and d) Cool Pockets

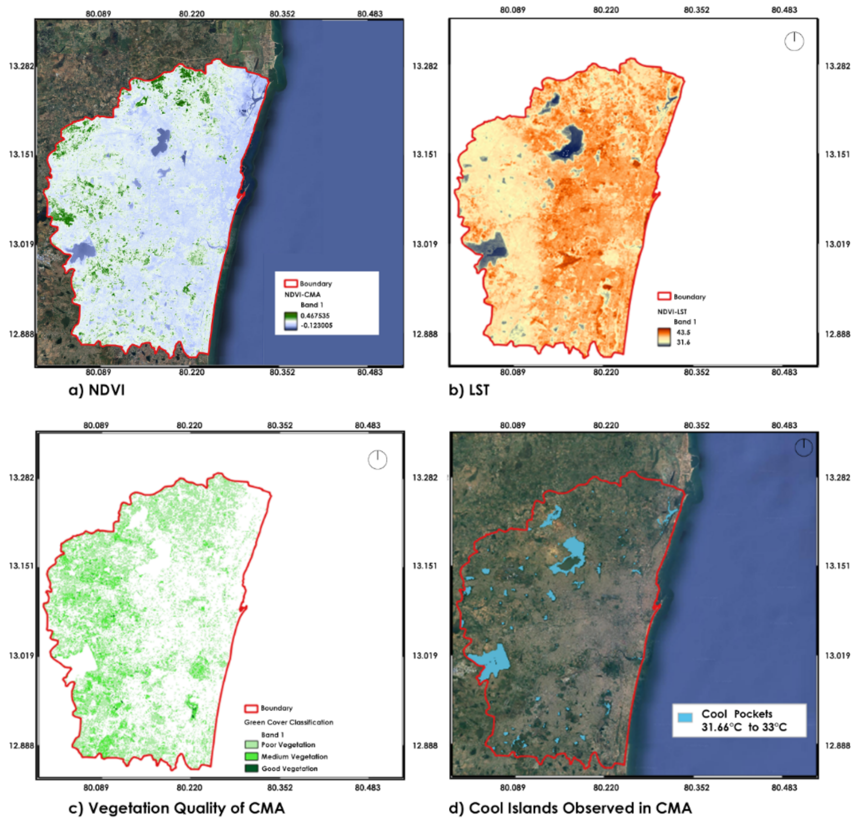

Fig 5. Map of CMA of May 2022, showing a) NDVI b) LST c) Vegetation Quality and d) Cool Pockets

3.2 LST and NDVI Observations for 2013 and 2022

The CMA region recorded a maximum LST of 37°C and a minimum LST of 23.63°C in the summer month of 2013. The minimum and maximum NDVI observed for the year 2013 is -0.11 and 0.49. Figure 4 shows the LST and NDVI map of June 2013. Through visual observations, it is noticed that the areas with higher vegetation have a lower LST. The LST map shows Heat Islands concentrated in the north-western and the south-eastern parts of CMA which are outside the limits of the GCC. The Heat islands in the northern eastern part of the city seem to be influenced by the lack of vegetation and due to industrial activities.

The LST for CMA for the year 2022, recorded a maximum temperature of 43.53°C and a minimum temperature of 31. 66°C. Also, the minimum and maximum NDVI observed for the year 2022 is -0.12 and 0.46. Figure 5 shows the LST and NDVI map of May 2022. Visual observations of the generated maps reveal that the LST is lower in regions with more vegetation. The LST map shows the heat islands are concentrated on the central, northern and parts of southern CMA. The western part of CMA is noticed to have lower LST in comparison to the other parts of the city due to the presence of vegetation.

This study has confirmed the negative association between LST and NDVI in the CMA. LST studies in the GCC have recorded minimum and maximum values of 27.12°C and 36.62°C in the year 2018[10] and 26.73°C and 40.75°C in the year 2020[9].

A study done for the CMA in the summer month of 2016 showed LST values between 27°C and 31°C with a mean LST of 28.86°C[11]. In this study, LST results for the year 2022 is found to be between 31.66°C and 43.53°C confirming the UHI phenomenon. This is further substantiated by a maximum increase of 6.53°C in LST from 2013 to 2022 within the CMA boundary.

3.3 Presence of Cool Pockets (2013-2022)

This study reveals that there is a presence of cool pockets associated with the natural systems of the city such as the city's rivers, lakes, marshes and the reserve forests. The cool pockets found in the CMA in 2013 and 2022 are shown in Figure 4 (d) and

Figure 5 (d). In the year 2013, cool pockets had a temperature range of 23.63 °C to 26 °C. Whereas in 2022, the number of cool pockets in the city has declined, with pockets having a temperature between 31.66°C and 33°C.

Urban thermal environments of coastal cities are influenced by the ocean. Qi et al (2022)[12] determined that, in coastal cities, the negative correlation between LST and NDVI is more evident in the inland zones that are more than 25km from the sea in summer. In these inland zones, the cooling effect of vegetation is more prominent. As Chennai is a coastal city and the major part of newly urbanized areas are in the inlands which are 30 to 40 km from the sea, the role of vegetation becomes even more significant in reducing UHI in CMA.

It is observed that the UHI studies done for the rapidly urbanising cities focus more on the urban heat islands and heat risk areas. However, there is a need to identify the cool pockets or areas with a cool island effect associated with the city. The cool pockets present around densely vegetated areas must be identified and appropriate strategies to protect the green cover from land use and land cover changes must be developed for conserving the microclimate associated with such cool pockets.

4 Conclusion

From the study, it is clear that the UHI effect in Chennai is becoming prominent in the growing city boundary of CMA with a maximum increase of 6.53°C in LST highlighting the need for mitigation strategies. Urban afforestation activities implemented in the Chennai Corporation area[9] are found to be effective in urban greening and such initiatives need to be expanded to the CMA as the loss in vegetation cover is 13.33% of the total CMA area. With thousands of acres of unused flat, concrete terraces of buildings in Chennai, rooftop gardening has the potential to increase the vegetation at the plot level in dense urban areas. Green roofs are found to be effective in reducing the Surface temperature by 1-2 °C[13]. The Chennai Resilience Strategy Report 2019 suggests the Urban Horticulture Initiative[14]and aims to have rooftop gardens in six lakh homes by 2030. This programme, if implemented, will significantly boost the amount of greenery in the CMA's rapidly developing areas. The Third Master Plan of Chennai which is under preparation should incorporate the concepts of "green pockets" and "protected green areas" to reduce UHI and enhance the urban microclimate[15].

The outcome of the study shows how effective and timely tracking of urban development characteristics and observing changes in the urban climate can be carried out using remote sensing and GIS technologies. It also stresses the need for appropriate interventions in terms of increasing urban vegetation and landscape planning to mitigate the UHI effect. Continuing studies investigating vegetation quality and its impact on LST are required to improve the composition and spatial distribution of vegetation within the cities. Urban planners and landscape architects can utilise this knowledge of how urban vegetation can lower the LST to make decisions on the urban vegetation and enhance the thermal environment of cities with similar characteristics.

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