Urban Climate Change in Populated Kathmandu Valley, Nepal: A Case Study

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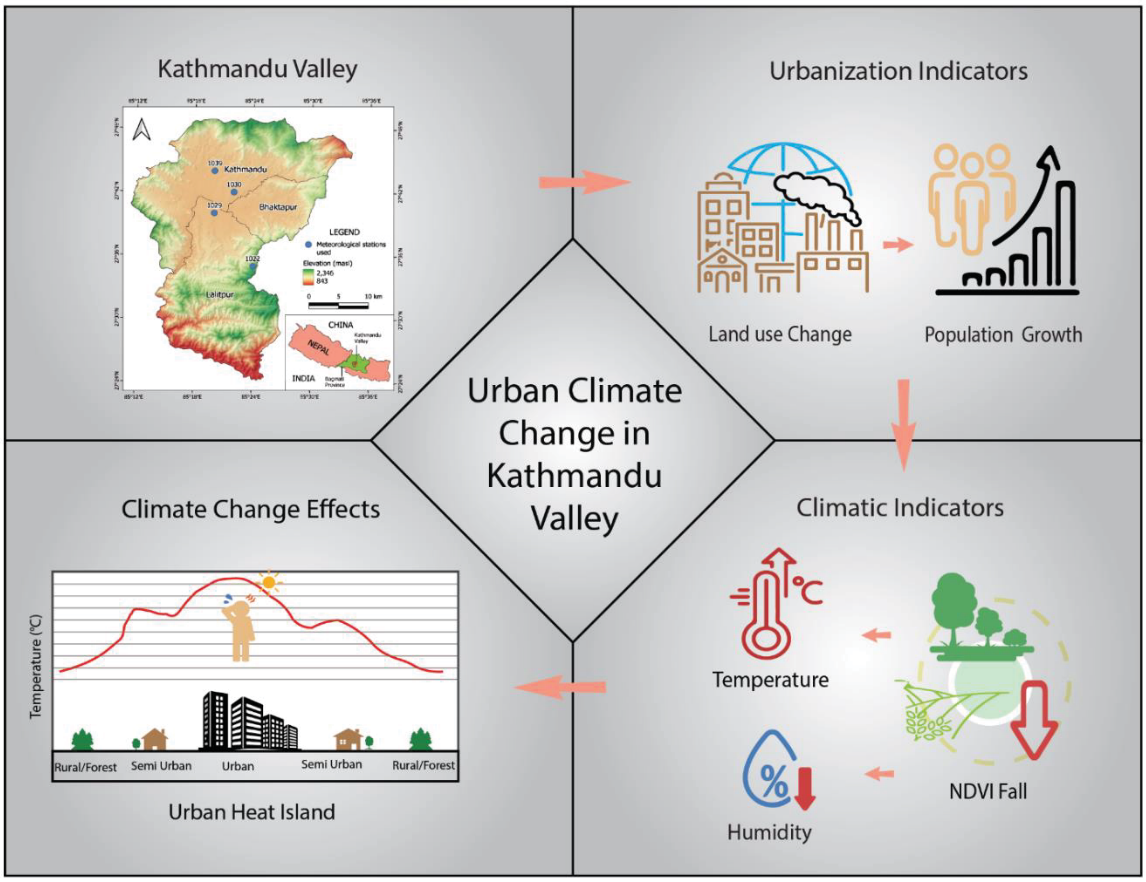
Abstract: Kathmandu Valley, the capital and commercial hub of Nepal, is experiencing rapid and unmanaged urbanization, leading to poor environmental conditions. The population, a key indicator of urbanization, has been growing at an average rate of 2.08% per year. This population growth from 1990 to 2021 has significantly altered land use, resulting in increased temperatures and transforming the valley into an Urban Heat Island (UHI). This study examines the effects of UHI by comparing normalized Land Surface Temperature (LST) in Kathmandu Valley and assessing the influence of land use changes on UHI intensity between 1990 and 2021. The result shows that built-up area has expanded by 30.7% of the total area, while the agricultural area has decreased by 33.59%. These changes in land use and land cover have caused a significant temperature increase at a rate of 0.038 °C per year. Green space density, measured by the Normalized Difference Vegetation Index (NDVI), has declined from 35.59% to 29.17%, being replaced by built-up areas. LST is inversely related to the presence of surface vegetation. The UHI phenomenon is observed to be stronger in urban centers such as Tribhuvan International Airport, Patan industrial area, Kritipur, and Kalanki, while it is weaker in semi-urban regions like Suryabinayak and Godawari. As climate change poses significant health and environmental challenges, adaptation has become a major issue for developing countries. Therefore, it is essential to implement change control and mitigation strategies specifically tailored to each urban region.

Keywords: Climate change, Urban heat island, Normalized Difference Vegetation Index, Land use land cover change

1. Introduction

Without any efforts to mitigate it, the global mean temperature is expected to rise anywhere from 2°C to 7.8°C by 2100 in comparison to the 1850–1900 reference period (Clarke et al., 2014). Global warming is defined as an increase in the global average surface air and sea surface temperature over the past 30 years (Ogunbode et al., 2019). Anthropogenic actions have been the major drivers of global warming by burning fossil fuels, farming livestock, and deforestation, which lead to the emission of greenhouse gases (GHGs). Every decade, human-induced warming has caused temperatures to increase by 0.2°C (likely between 0.1°C and 0.3°C), and in 2017, this warming reached about 1° C above pre-industrial levels (Allen et al., 2018). With 20 to 40% of the world's population already experiencing temperatures beyond 1.5 °C in at least one season, many regions of the world are already experiencing increased global warming on a regional scale. (IPCC, 2014).



Urban areas, a major source of greenhouse emissions, have a direct influence on local and global climate and act as a host for global environmental implications (Grimm et al., 2008). Rapid urbanization around the world has prompted to a number of problems for humanity, most notably climate change. Extreme challenges in managing the environmental risks and impacts have been faced, especially in developing countries which have seen huge economic and social development due to urbanization. Urban areas consume land directly as their physical footprint expands, often resulting in a complete change in the landscape by reducing greenery and increasing the impervious surfaces (Bai et al., 2014; Jiang et al., 2012; Lopez et al., 2001). This process alters the local climate, moisture exchange, and ecosystem services, favoring heat-trapping and storage. It also modifies land use, land cover, and land surface features (Cui et al., 2016). This alteration of the surface and atmospheric characteristics consequently modifies the local atmospheric variables of the surroundings, changing the region's hydrology and climate (Kalnay and Cai, 2003; McDonald et al., 2016; Seto and Shepherd, 2009). Thus, significant changes in the local climate are observed; warmer temperatures, altered winds, urban-modified clouds and precipitation, foul air, and water quality, as well as high-impact extreme weather events. This is termed urban climate change.

It is commonly acknowledged that one of the main causes of global climate change is the change in land use and land cover (LULC) at the local, regional, and global levels (Foley et al., 2005; Pielke, 2005). Several studies have shown that anthropogenic LULCs are one of the key factors affecting the climate of the regions (Kalnay and Cai, 2003; Paeth et al., 2009; Taylor et al., 2002). The study of Kalnay and Cai (2003) was carried out in the US which compared the surrounding rural area with the observing urban city to study the impact of urbanization. The LULC change resulted in 0.27 °C mean surface warming which is higher than past projection based on urbanization. Using a climate model for future pathways, Paeth et al. (2009) found a prominent surface heating and weakening of the hydrological cycle in the study area i.e., tropical Africa which enhanced the heat stress. This study also showed that land use changes are responsible mainly for simulated climate response. For the analysis of LULC change, Taylor et al. (2002) used the General Circulation model which showed 4% of tree cover being converted to bare soil in 35 years prior to 1996. Through its influence on the biogeophysical system, land use change also has a considerable effect on the climate system. Roughness, surface albedo, soil moisture, vegetation cover, and other biogeophysical feedback mechanisms essentially have an impact on the earth's surface, which in turn influences the processes that transfer radiation, heat, and water between the surface and atmosphere (Crutzen and Andreae, 1990). These effects are directly linked to changes in surface temperature, humidity, wind speed, and precipitation, making large-scale climates more complex (Deng et al., 2013; Deng et al., 2014). Surface temperature and precipitation serve as direct indicators of biogeophysical feedback mechanisms, making them valuable observational data that are frequently utilized in the assessment of climate change (Ding and Shi, 2013; Junkermann et al., 2009; Wang and Ge, 2012; Woldemichael et al., 2014).

An "Urban Heat Island (UHI)" is a phenomenon in which temperature discrepancies between urban and nearby rural areas result from heat-trapping, with urban areas experiencing greater temperatures than rural areas (Jin et al., 2005). In comparison to nearby areas with existing vegetation, this effect causes greater absorption of electromagnetic energy and slower cooling of urbanized surfaces (Imhoff, 2010). The importance of this issue has prompted more research into the origins and consequences of UHI, including an examination of temperature variations in metropolitan areas and the underlying mechanisms (Chidi et al., 2021; Nuruzzaman, 2015; Santamouris, 2007; Yang et al., 2016). The study by Chidi et al. (2021) has concluded that built-up areas contributed highly to increasing LST and new built-up has higher LST than compared to other land cover surfaces. Poor urban design, air pollution, changes in surface area, and other variables all contribute to the continuing process known as UHI (Nuruzzaman, 2015). The study carried out research in Europe by Santamouri. (2007) found out that the parameters involved in the intensity of UHI are wind, cloud cover, moreover by cyclonic and anti-cyclonic conditions. Additionally, high solar reflectance and infrared emittance values are examples of cool materials that may help to lower urban ambient temperatures and lessen the impact of heat islands. UHI-related effects change the soil characteristics, biogeochemical cycles, energy metabolism, and the health of local populations. Concerns about the authenticity of this research have been raised in numerous investigations, particularly in relation to the measurement, characterization, and reporting of heat island magnitudes (Santamouris, 2015; Stewart, 2011). Santamouris (2015) compiled, analyzed, and presented the heat island magnitude information of 101 cities and regions of Australia and Asia. The studies showed that non-standard measuring instruments usually report higher urban heat island magnitude than standard fixed measuring stations and instruments. Stewart (2011) critically assessed the quality of the methodology with 190 heat island study samples, using nine experimental designs and communication criteria. The results of this evaluation are disappointing. The sample's average quality score is only 50%, and over half of the reported urban heat island magnitudes are deemed to be unreliable from a scientific standpoint.

Today, developing countries confront more issues from urbanization than developed nations. Recently, the highest rate of urbanization is reported in Asia and Africa (ADB, 2005; Lall et al., 2017). Asian cities are urbanizing faster with the urban proportion increasing by 1.1% annually between 2015 and 2020 (UNDESA 2019). Around 232 million people, or 17% of the population, in Asia, lived in urban areas in 1950. 2.664 billion people, or about 55% of the Asian population, are projected to live in cities by 2030, a rise of more than 70%, or 1.1 billion, over the following 25 years (WPP, 2005; UNDP, 2005).

In the context of Nepal, urbanization has been observed since 1970 (Rimal et al., 2017). With an annual increase of 3.0% over the past few decades, Nepal has been one of the nations that is quickly urbanizing, and this trend is anticipated to remain until 2050 (Bakrania, 2015). With a population of more than three million, Kathmandu Valley is a significant metropolitan hub and is by no means an exception (Chitrakar et al., 2017). The rapid transformation of the agriculturally-dominated valley into an impervious concrete surface layer throughout previous few decades has resulted in significant changes to the climate and weather in the Kathmandu Valley (Maharjan and Regmi, 2014). Understanding the effects of LULC's transition is crucial since between 2010 and 2014, the Kathmandu Valley's urban development rate was 3.94%, resulting in significant landscape alterations (UNDESA, 2015).

In spite of such increasing population and urban areas, there has been limited research carried out on Kathmandu Valley to date. For example, Joshi et al. (2021) analyzed the land use changes in Chandragiri and Kathmandu from 1996-2017 which shows a 3.68% increase in built-up areas. Additionally, Thapa and Murayama (2009) analyzed the LULC change patterns of Kathmandu Valley from 1967 to 2000. They observed that, particularly after the 1980s, urban expansion accelerated. These studies clearly point towards an unmistakable UHI effect in Kathmandu Valley, but only a handful of researchers have incorporated the effects of changing land use on the valley's UHI intensity (Baniya et al., 2018; Chidi et al., 2021; Sarif et al., 2020). Baniya et al. (2018) analyzed LULC change and found that NDVI was low and Normalized Difference Built-up Index (NDBI) was high in urban areas that create a possible risk of UHI. Similarly, the change in land use pattern into impervious surfaces grew by 113.44 km^2 with the loss of 118.29 km^2 of agricultural land and the lower temperature was observed outward of the city center and higher in the core of the Kathmandu Valley (Sarif et al., 2020). The concrete jungle can be attributed to the elevated temperature that the valley is experiencing at present.

Therefore, this paper aims to provide details of the land use and UHI effect in Kathmandu Valley, which has both research and policy-level-based applications. To complement UHI analysis, the authors have considered the combined effect of two additional indices lacking in previous studies, the Urban Thermal Field Variance Index (UTFVI) that quantifies UHI at the district level (Ahmed, 2018; O'Loughlin et al., 2012; Patz et al., 2005; Santamouris et al., 2015) and Discomfort Index (DI) that estimates the impact of temperature on human health and comfort (Poupkou et al., 2011; Pal and Ziaul, 2017). Many studies have individually highlighted the increasing climatic change, temperature, and its impact on people and the environment, which do not address the environmental and health implications of multiple urban climate change indices in rapidly urbanizing cities like Kathmandu Valley, which this paper targets to fulfil. Moreover, the objective of this research is to demonstrate urbanization patterns and their environmental implications, analyze the temperature trend of Kathmandu, estimate the UHI effect on climate change and human response to climate change adaptation, and mitigation of environmental complications. The collected data and the findings from this study can be useful for city planners and policymakers in dense urban cities of many developing countries and support implementing mitigative measures.

2. Data Sets and Methods

2.1 Study Area

Kathmandu Valley is located at a latitude of 27°38'32"- 27°45'7" N and a longitude of 85°16'5"- 85°22'32" E (Figure 3) (Thapa et al., 2008). From 1,100 to 2,346 meters (on average 1350 meters) above mean sea level, the bowl-shaped valley's elevation ranges (Chitrakar et al., 2017). The valley consists of the Kathmandu, Lalitpur, and Bhaktapur districts, which cover 899 square kilometers having a population density of 2793 per square kilometer (Britannica, 2024). The valley is a cultural and political hub of Nepal. It has a mild, and generally warm and temperate climate with an average annual temperature of 16.1ºC (Sunheron, 2024). The average humidity of the city is about 75% and the annual precipitation received is 2812 mm. Summer rains are heavier than winter influenced by southwest monsoon winds.

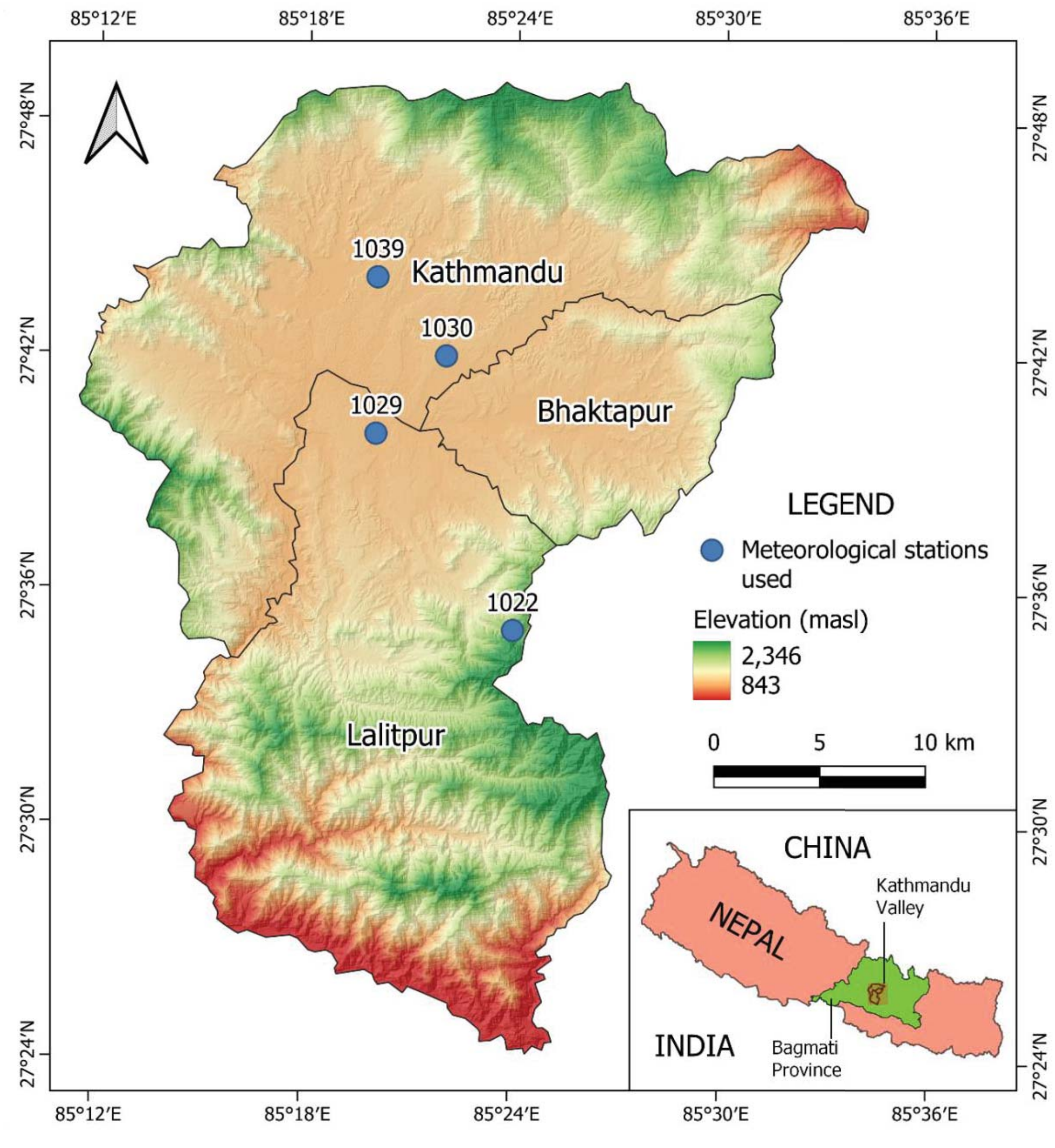


Figure 3. Selected study area and meteorological stations

2.2 Data Sources

2.2.1 Satellite Image Data

A series of satellite images were used for retrieving LULC, NDVI, LST, UTFVI and UHI maps. The methodological flowchart for processing of these indices is presented in (Figure 4). Landsat satellite images were acquired from the freely available U.S. Geological Survey. The details of the images are presented in (Table 1).

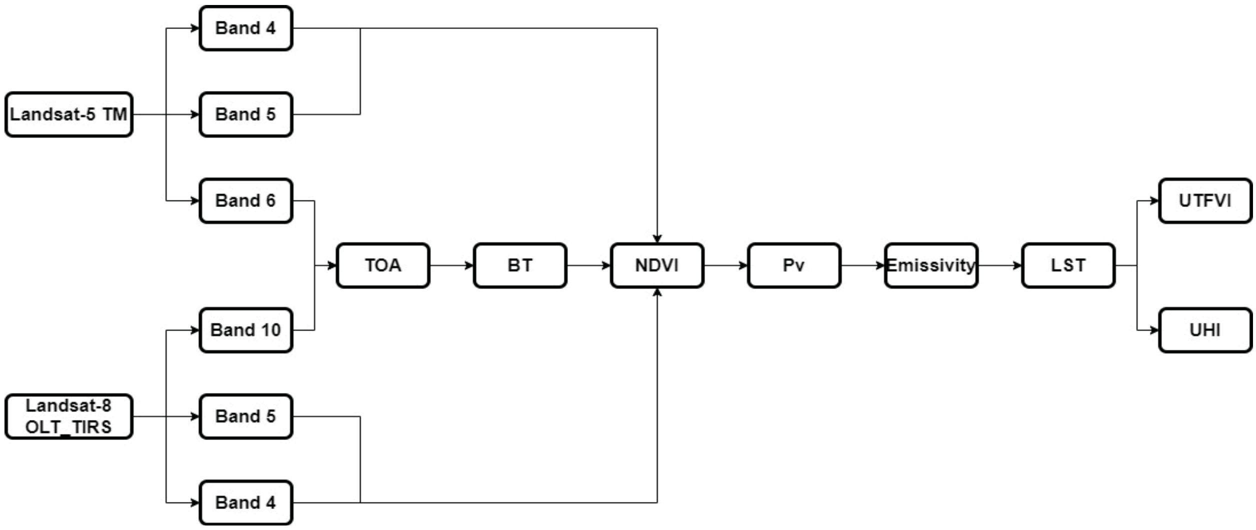


Figure 4. Satellite data processing flowchart where, TOA: Top of Atmospheric, BT: Brightness Temperature Conversion, and Pv: Proportion of Vegetation.

Table 1. Details of the Landsat data

Satellite ID	Sensor	Path/row*	Acquisition Date
Landsat-8	OLI_TIRS	141/41	11/8/2021 12/5/2020 11/26/2019
Landsat-5	TM		11/22/1992 11/25/1991 11/19/1990

**Path/row is listed according to Worldwide Referencing System (WRS-2) for both OLS_TIRS and TM sensors. Source: USGS- U.S Geological Survey, 2022*

2.3 Other Auxiliary Data

The shape file used for the selected study area was obtained from Survey Department. Similarly, social statistical data such as registered population, population density, and growth rates for the years 1991 and 2021 (CBS, 2022) for Kathmandu, Bhaktapur and Lalitpur districts were taken from the Central Bureau of Statistics (CBS). Furthermore, climatic data which includes temperature and relative humidity of 4 different metrological stations, Kathmandu airport, Panipokhari, Khumaltar, and Godawari, were taken from the Department of Hydrology and Meteorology (DHM). Panipokhari, Kathmandu Airport, and Khumaltar stations were considered as urban areas whereas Godawari was considered a semi-urban area for UHI analysis.

2.3.1 Change in population density

Population density of all three districts, Kathmandu, Bhaktapur, and Lalitpur was calculated by dividing the total population in each district by respective areas in the respective years 1991 and 2021. Moreover, the trend of population growth was plotted on the graph and analyzed.

2.3.2 Temperature trend

On the basis of data acquired from DHM, temperature, and humidity trends were calculated for which a non-parametric test was done using the Mann Kendal test and Sen's Slope statistics. The graphs of the trend of average temperature, maximum temperature, minimum temperature, and humidity were also plotted and analyzed. Normalizing LST from spectral data allowed for the examination of the UHI phenomenon, which was then further confirmed by temperature trend analysis.

2.3.3 LST Retrieval

LANDSAT-5 MMS_TM and LANDSAT-8 OLI_TIRS images were used for calculating the LST of the years 1990 and 2021 respectively. LST was calculated using QGIS 3.16.15 software, which includes a number of intermediate outputs, including Atmospheric Radiance, Atmospheric Brightness, NDVI, Proportion of Vegetation, and Emissivity, which is measured using Eqs. (1)-(6). Based on the Planks law, top-of-atmospheric (TOA) spectral radiances are measured through satellite thermal infrared sensors. The radiance emitted from the earth's surface, upwelling radiance from the atmosphere, and down welling radiance from the sky resulted from the TOA radiance for which Eq. (1) was used (USGS, 2015). Using the thermal constants, the band data was converted to Brightness Temperature (BT) after conversion to sensor spectral radiance. For calculating BT, Eq. (2) was used (USGS, 2015).

NDVI is the quantitative and qualitative index (Kross et al., 2015) used to evaluate the density of green space (Weier and Herring, 2000), fractional vegetation cover (Wanjuan et al., 2017), and the response of ecology to environmental change. Its value varies between -1 to +1. Low NDVI (negative or near zero) indicates a region with no vegetation, highly built up, barren area, or water (-1) whereas a higher value indicates a higher density of green vegetation (Hashim et al., 2019). NDVI was computed using Eq. (3) (Lillesand et al., 2007).

LST was calculated using QGIS 3.16.15 software, which includes a number of intermediate outputs, including Atmospheric Radiance, Atmospheric Brightness, NDVI, Proportion of Vegetation, and Emissivity, which is measured using equations. To make this correction spectral emissivity was calculated using Eq. (5). For calculating emissivity, an intermediate calculation for the Proportion of vegetation was made using Eq. (4). Ultimately, Eq. (6) was used for computing LST (Artis and Carnahan, 1982; Das, 2015).

$$TOA(L) = \mathrm{M_L} * \mathrm{Q_{cal}} + \mathrm{A_L} \quad (1)$$

$$BT = \left(\frac{K_2}{L_n\left(\frac{K_1}{TOA}\right) + 1} \right) - 273.15 \quad (2)$$

$$NDVI = \frac{(Band\ 5 - Band\ 4)}{(Band\ 5 + Band\ 4)} \quad (3)$$

$$P_v = Square\left(\frac{(NDVI - NDVImin)}{NDVImax - NDVImin} \right) \quad (4)$$

$$\varepsilon = 0.004 * P_v + 0.986 \quad (5)$$

$$LST = \left(\frac{BT}{1 + \left(A * \frac{BT}{1.4388}\right) * Ln(E)} \right) \quad (6)$$

2.3.4 Normalizing LST for UHI and UTFVI Retrieval

The normalization method described by Eq. (7) was used to compare LST at various research areas (Abutableb et al., 2015). Furthermore, the study area is classified into two classes as area with UHI (normalized LST >1.5˚C) and without UHI (normalized LST <1.5˚C).

$$UHI = \frac{(T_s - T_{mean})}{SD} \qquad (7)$$

where, T_s (Celsius) is the land surface temperature, T_{mean} (Celsius) is the mean of the land surface temperature, and SD is the standard deviation.

Similarly, UTFVI quantitatively analyzes the urban heat island effect (Ahmed, 2018). The calculation for UTFVI was made using the Eq. (8) as:

$$UTFVI = \frac{T_s - T_{mean}}{T_s} \qquad (8)$$

where, Ts (Kelvin) is the land surface temperature, T_{mean} (Kelvin) is the mean of land surface temperature, and SD is the standard deviation.

Table 2. Classification of UTFVI Index (Source: Liu and Zhang, 2011)

UTFVI	UHI Phenomenon	Ecological evaluation index
<0	None	Excellent
.000-.005	Weak	Good
.005-.010	Middle	Normal
.010-.015	Strong	Bad
.015-.020	Stronger	Worse
>.020	Strongest	Worst

2.3.5 Discomfort Index

The Discomfort Index (DI), one of the indicators based on the basic environmental parameters of temperature and relative humidity, estimates the combined contribution of temperature and relative humidity to human thermal comfort (Poupkou et al., 2011). In this study, Thom's DI was calculated using Eq. (9) (Thom, 1959). The obtained results were further analyzed for different level of comfort conditions (Yousif and Tahie, 2013) as shown in Table 4.

$$DI = T - (0.55 - 0.0055RH)(T - 14.5) \qquad (9)$$

where, DI= Discomfort Index, T=Mean air temperature in ˚C, RH= Average relative humidity (%) (Yousif and Tahie, 2013; Assael et al., 2010).

3. Results and Discussion

Population and land use change pattern was analyzed as indicators of urbanization in Kathmandu Valley and spectral analysis of NDVI change was made to observe a loss in vegetation over 30 years. Temperature data from different ground metrological stations were put together to analyze the temperature growth trend and variation between urban and semi-urban temperatures to observe the formation of UHI which was further verified from the spectral analysis of LST. Similarly, UHI effects and the ecological conditions of Kathmandu Valley were qualitatively analyzed through the UTFVI model. Furthermore, the health implications of climate change were analyzed through discomfort index as calculated from above equations whose results are discussed below.

3.1 Urbanization

3.1.1 Population and Population density

The population shift from 1991 to 2021 is shown in Figure 3, with the Kathmandu district observing the most change. The population density of Kathmandu valley has changed from 1230 per sq km in 1991 to 3333 per sq km in 2021. The high growth rate suggests rapid urbanization of Kathmandu valley. The Kathmandu Valley, with approximate population growth from 1.1 million in 1991 to 3 million in 2021, averaged growth of 2.08% per year (CBS, 2022). About 10.3% of the total national population resides here (CBS, 2022). The better economic opportunities, basic services, and living standards available in comparison to rural areas influenced this growth which ultimately controls the LULC. This has flagged that decentralization of facilities and development infrastructures in developing countries can potentially help to reduce migration to an urbanized area. Furthermore, the fact that Bhaktapur district has the highest growth rate of 3.32% per year (CBS, 2022) verifies the urban sprawl which is responsible for the replacement of cultivable land by built up area. High population density at the core of the city enhances more LULC which ultimately governs the formation of UHI. Population is one of the major indicators of urbanization as increase in population triggers other indicators such as land use, energy consumption, water supply, Gross Domestic Product (GDP), living standard of people, number of operating vehicles, etc. which ultimately is responsible for high production of waste water, night soil, pollution and GHGs (Cui and Shi, 2012).

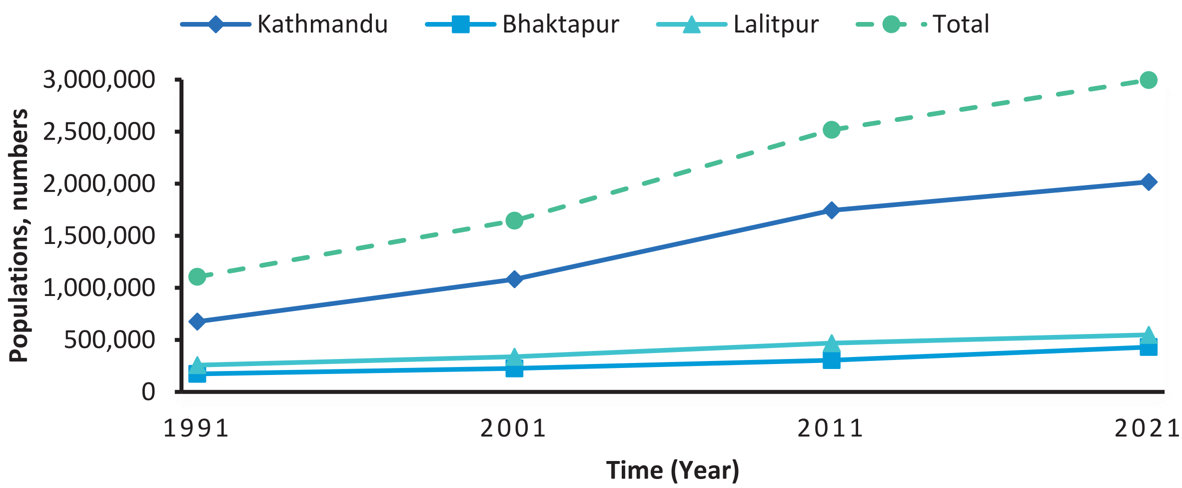


Figure 5. Trend of population of Kathmandu Valley over the last years (1990-2021)

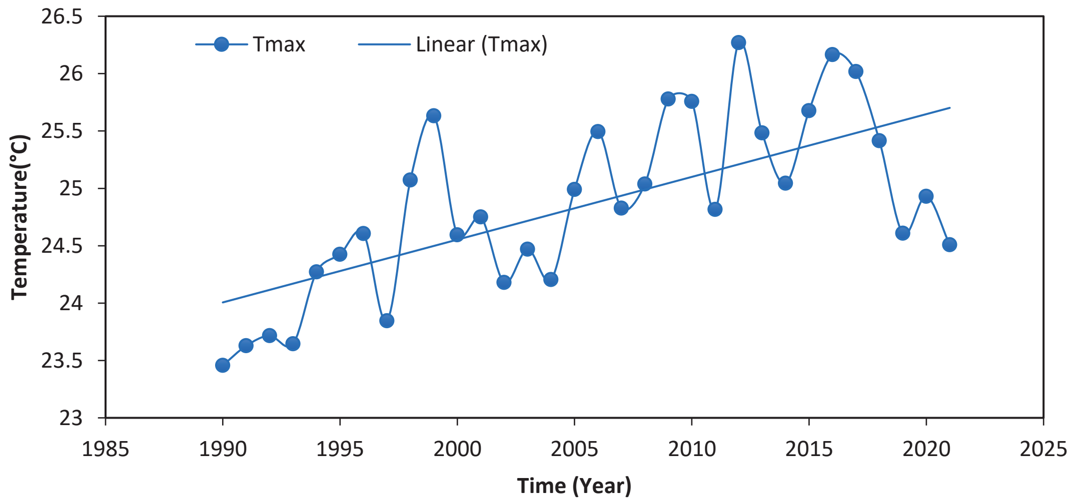
3.1.2 Temperature Trend and Humidity Changes

The significant increase in temperature can be observed on the basis of annual average air temperature data obtained from metrological stations (Table 3). The Kathmandu Valley's average, maximum, and minimum temperatures have all increased significantly over the past year at rates of 0.038°C yr^{-1} (p .0001), 0.055°C yr^{-1} (p 0.05), and 0.02°C yr^{-1} (p 0.0001, respectively) (Figure 6). The average temperature of the station at Kathmandu airport, which is at the urban center of the study area, was observed to be high (19.3 ºC) during the summer season (June, July, and August). Godawari, a semi-urban station, shows a low (16.8 °C) average temperature in comparison, the temperature in urban areas is high i.e. Kathmandu airport (19.3°C), Khumaltar

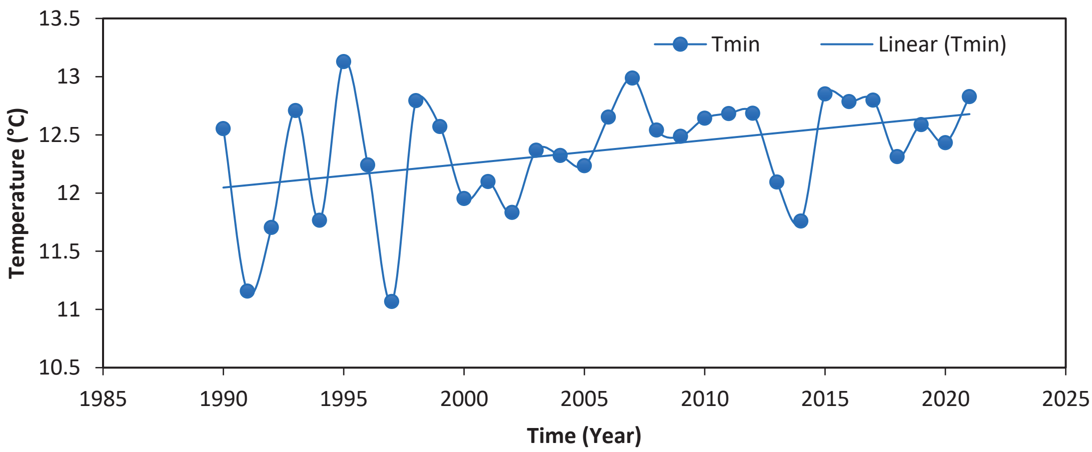
(18.4°C) and Panipokhari (19.9°C) As a phenomenon there was a formation of UHI at the core of the valley. Additionally, the mean annual humidity shows a declining trend of 2.3% per decade (Figure 7). Similar research was conducted in the Kathmandu Valley by Thapa et al. (2021), who found that the annual average minimum and maximum air temperature trends are trending slightly upward at 0.04 °C/year and 0.097 °C/year, respectively (Thapa et al., 2021). Along with the increasing trend of temperature, the decreasing trend of RH makes the air even drier which enhances the evaporation rate which causes scarcity of moisture on the surface, ultimately affecting the vegetation and rainfall patterns (Denson et al., 2021).

Table 3. The detail of meteorological stations and annual temperature (°C) of period 1990-2021

St. ID.	Station Name	Longitude (Degree)	Latitude (Degree)	Altitude (m)	Average temp(°C)	Maximum temp(°C)	Minimum temp(°C)
1030	Kathmandu Airport	85.35625	27.70383	1337	19.3	27.4	11.2
1029	Khumaltar	85.32578	27.65175	1334	18.4	25.8	11
1039	Panipokhari	85.32415	27.72864	1329	19.9	30.1	9.7
1022	Godawari	85.37883	27.59292	1527	16.9	24.3	9.5



(a)



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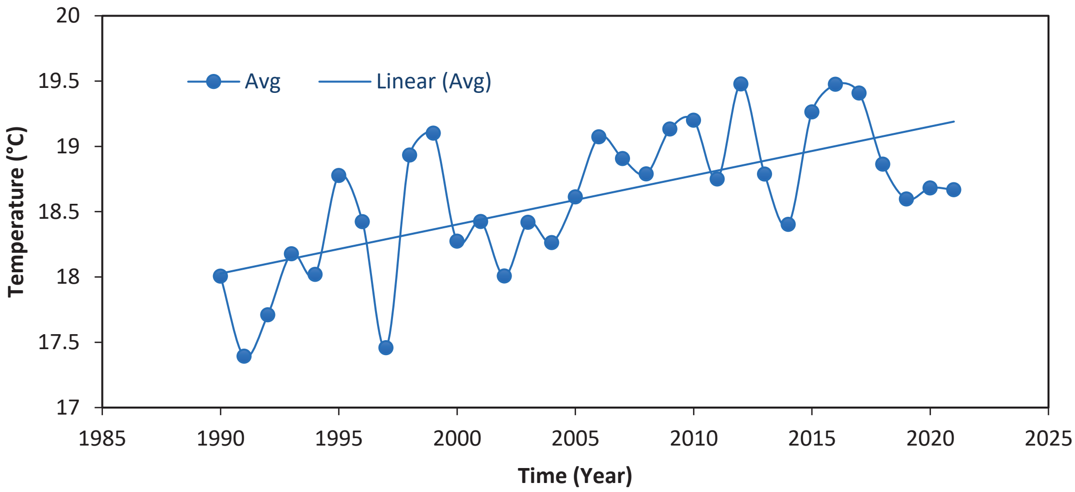

(c)

Figure 6. Trend value of the (a) maximum, (b) minimum and (c) average of temperature trend of period 1990-2021

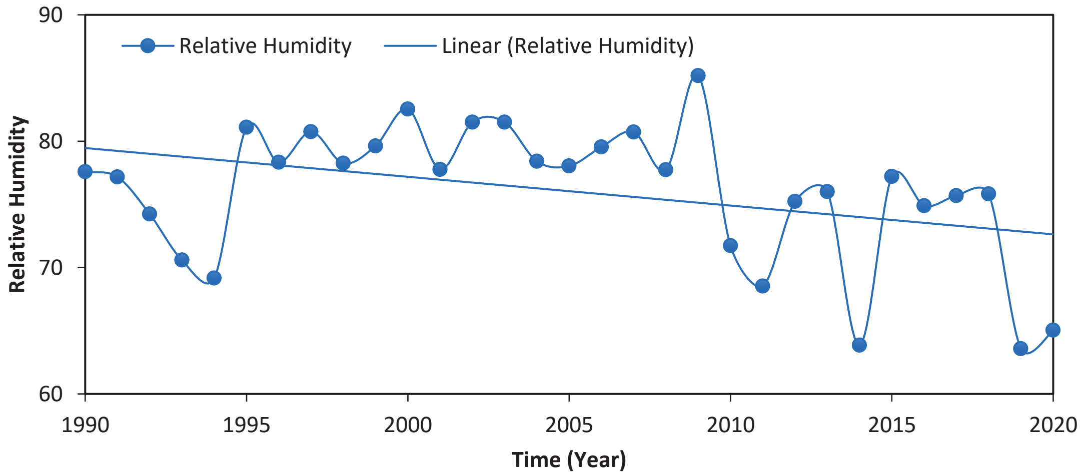

Figure 7. Trend Value of the Kathmandu Valley over the Past Year

3.1.3 Change of Land Use and Land Cover

For the analysis, we used USGS Earth Explorer, to identify seven land use clusters (Figure 8 and Figure 9), namely, shrubland, grassland, agricultural land, barren area, water bodies, and built-up area. Figure 8 shows a highly urbanized area at the center of the valley in the spatial distribution of land use land cover map of Kathmandu Valley of 1990 and 2020. The built-up area significantly increased by 30.7% of the total area towards the periphery, while the agricultural area shrunk by 33.59%. The change in water bodies, barren land, grassland, and shrub land is significantly less. The rapid LULC directly affects the land resources mainly due to the expansion of urban or built-up areas and the reduction of agricultural and vegetation land. As indicated as a percentage change in (Figure 7), built-up area has displaced vegetation and agricultural land in the past three decades, from 1990 to 2020, at a rate of 95.7 square kilometers each decade.

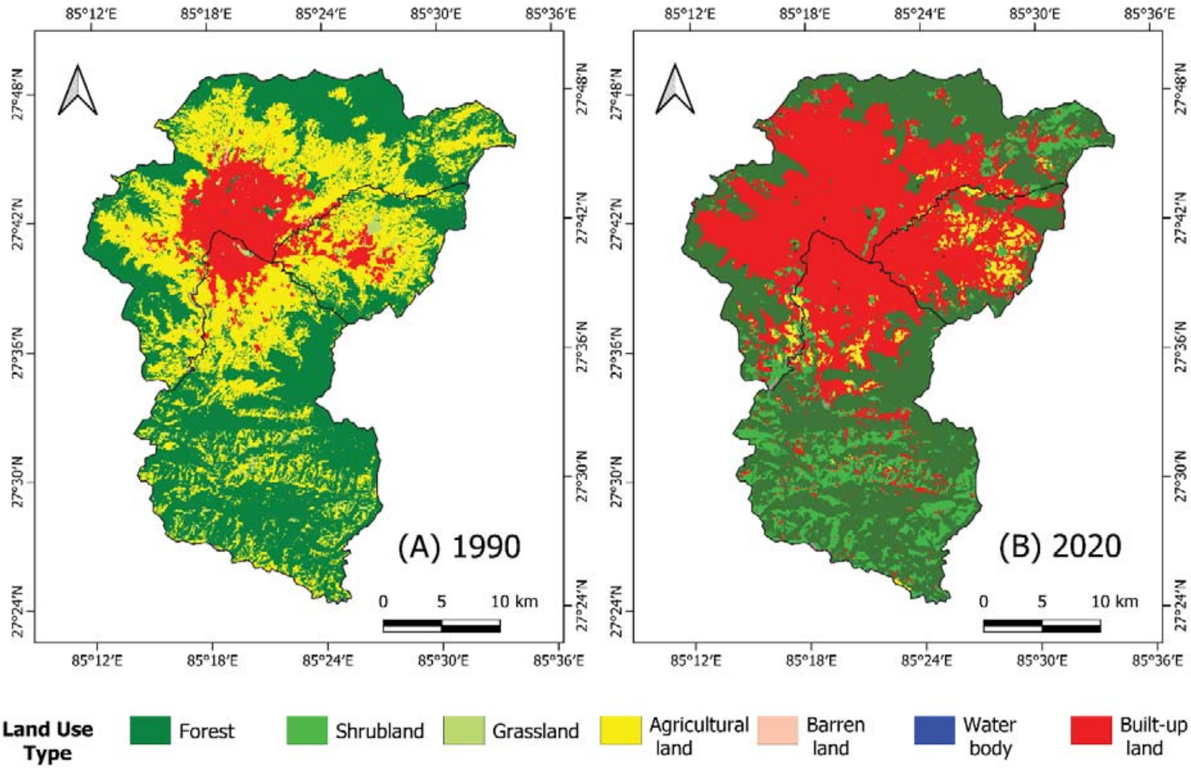

Figure 8. Land Use Land Cover Derived from Landsat Remote Sensing

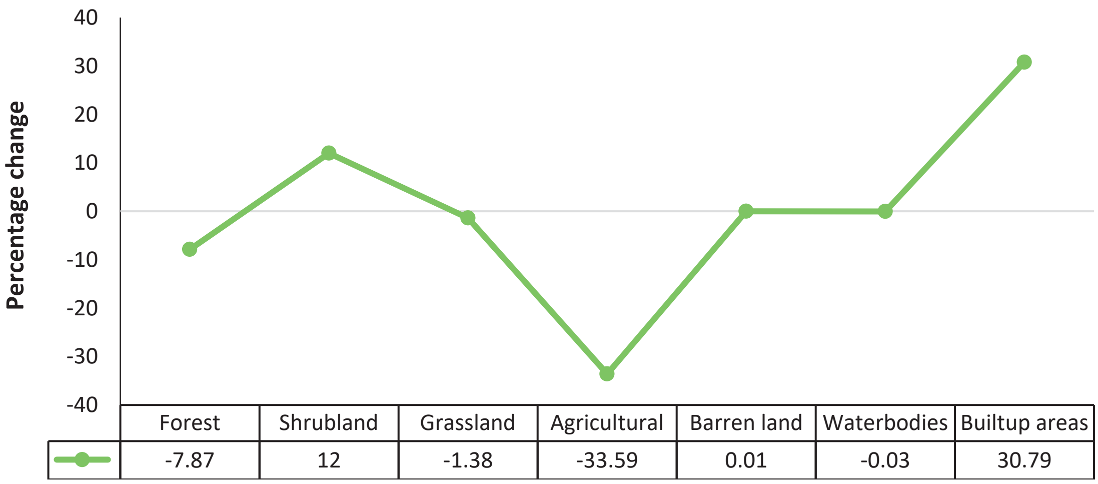

Figure 9. Percentage Change in Land Use of Kathmandu Valley during 1990-2021

3.2 Climatic Effects of Urbanization

3.2.1 NDVI

In order to access environmental and climatic change in the Kathmandu Valley, the NDVI, one of the indices frequently employed for emphasizing vegetation-bearing areas on a remote sensing scene, was calculated. On analysis from Eq. (3), the area with higher mean annual NDVI (0.2 to 1) has decreased from almost 35.59% to 29.17% whereas the area with lower mean annual NDVI (-1 to 0.2) has increased from 73.47% to 83.41% (Figure 10), which ultimately signifies replacement of green land by a built-up cover during this period (Hashim et al., 2019). Moreover, notable differences can be seen in the core of the valley. Rapid urbanization immediately impacts vegetation covering due to the overuse of resources, which in turn affects the NDVI (Cui and Shi, 2012). Furthermore, the reduction in NDVI during 1990-2021 is responsible for decrement in precipitation and increment in LST in Kathmandu Valley (Bhandari and Kumar, 2012; Ghebrezgabher et al., 2020).

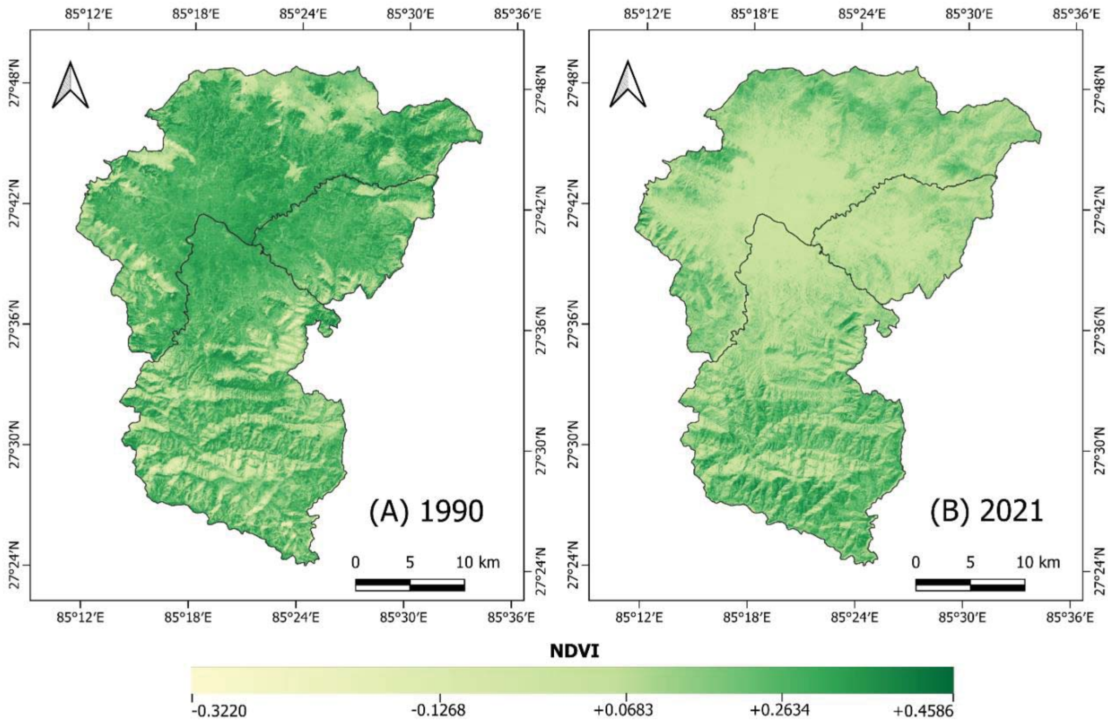

Figure 10. Mean Annual NDVI during period (a) 1990-1992 and (b) 2019- 2021

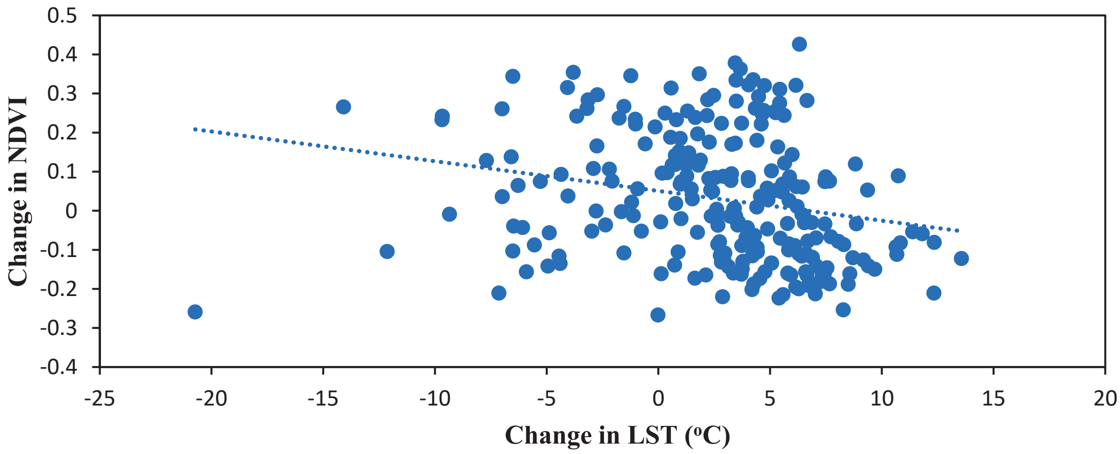

Figure 11. Correlation between Change of LST and NDVI during 1990 and 2021

On correlation and regression analysis between the change of NDVI and LST during 1990-2021 to analyze the temporal change and vegetation cover, the value of the correlation coefficient was -0.228 and slope -0.0076 (Figure 11). The negative correlation coefficient and slope show the inverse relation between LST and NDVI which signifies that the regions having less vegetation have a higher surface temperature. Moreover, a higher rate of urban sprawl has been observed in the regions with less surface temperature and higher vegetation cover, which was ultimately replaced with urbanized regions, during 1990-2021, causing an increase in surface temperature.

3.2.2 Land Surface Temperature

The land surface temperature of Kathmandu valley was calculated as explained in section 2. Figure 12 shows the spatial distribution of LST of Kathmandu valley between 1990 and 2021. The results suggest that the LST in the Kathmandu valley was greater in the most urbanized central area than in the surroundings, thereby demonstrating that the type of land cover in an area has a dramatic effect on how the LST is distributed. The comparative analysis of LST distribution between 1990 and 2021 clearly shows the expansion of regions with higher LST which further projects the increasing temperature trend of nearby semi-urban regions if the same pattern continues. Moreover, the average temperature was 13.4 °C and 16.34 °C in 1990 and 2021 respectively, which indicates a rise of about 3 °C.

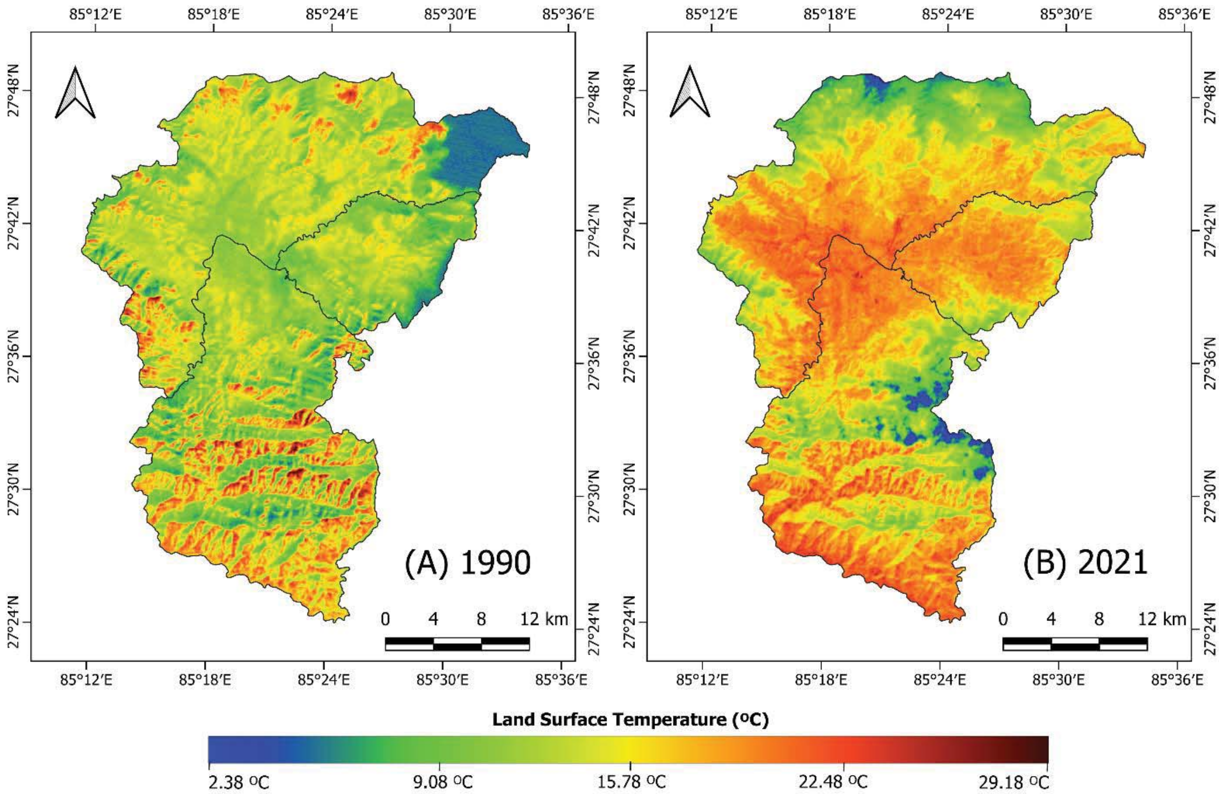

Figure 12. LST Distribution over Kathmandu Valley during (a) 1990 and (b) 2021

3.2.3 UHI and its Ecological Effects

The areas with normalized LST values greater than 1.5 °C above the mean of land surface temperature are referred to as the UHI in the research area. Due to the dense population and buildings in urban regions, there is a lot of anthropogenic heat released through cars, air conditioners, and other heat sources as well as heat stored and radiated by huge, intricate, and impermeable urban structures (Rizwan et al., 2008). In order to identify them, it is helpful to describe the causal elements that led to the development of UHI. Urbanization indices and the UHI index are closely correlated. The expansion of the population, the quick rise in GDP, the paving of more roads and buildings, the number of operating buses, and the shrinkage of arable land have all significantly contributed to the growth of UHI. According to Cao et al. (2016), due to their effects on rising energy consumption and/or impervious surface, population growth and agglomeration, built-up area growth, and housing density increases are significant drivers of UHI in the Kathmandu Valley. Figure 13 shows the significant change in UTFVI in Kathmandu valley during 1990-2021. Figure 11 demonstrates how the weak UHI phenomenon in a location has been replaced by a stronger UHI phenomenon during a 30-year period. Similarly, the ecological condition has been degraded from good to worse which has been caused due to rapid and unmanaged urbanization.

Furthermore, to investigate the formation of UHI in Kathmandu valley, Figure 14 shows the different regions with and without UHI. It is observed that there is a formation of heat islands around Tribhuwan International Airport, Patan industrial area, Kritipur, and Kalanki (annotated 1,2, and 5 in figure respectively) which are in the core region of the city. A cooler setting was detected around Suryabinayak and Godawari (annotated 3 and 4 respectively) which are in the peripheral regions of the valley and are areas with high vegetation. As vegetation has a cool effect on UHI and temperature increases, the peripheral semi-urban region shows less effect of UHI.

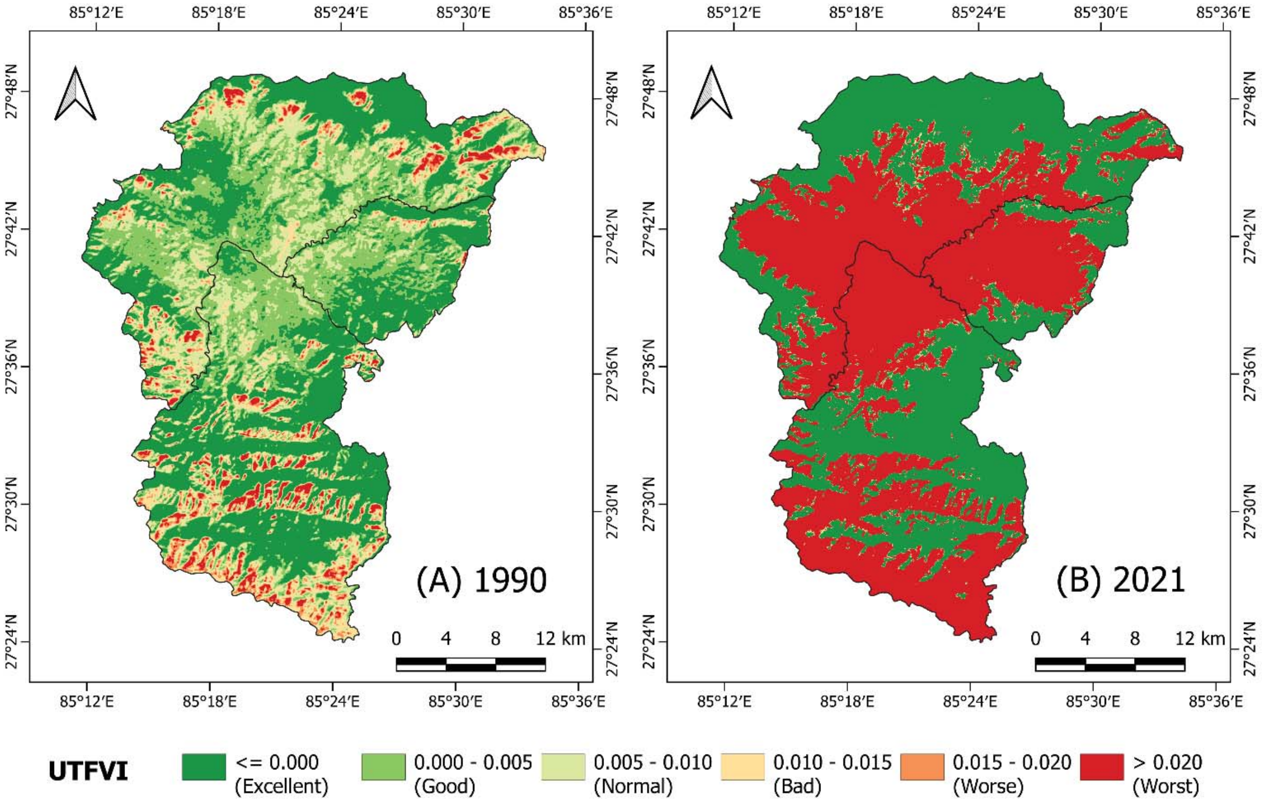

Figure 13. UTFVI of Kathmandu Valley during 1990 and 2021

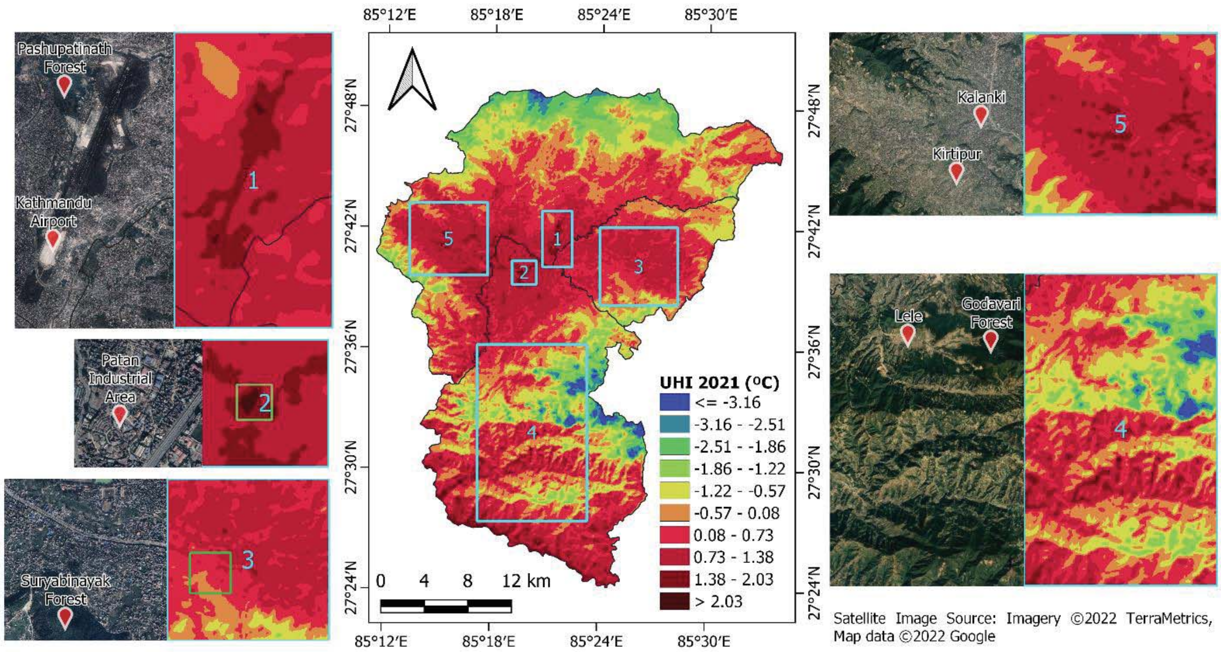

Figure 14. UHI in Kathmandu Valley of 2021

3.3 Discomfort Index and Health Implications of Urban Climate Change

The linear trend of DI change over the years, starting in 2007 and increasing until the value of DI above the threshold of 24, indicating that over 50% of people report experiencing pain, as illustrated in Figure 13.DI calculated, considering the average temperature and average humidity of Kathmandu, analysis from Table 4 over 50 % of the population feels thermal discomfort in 2021 whereas fewer than 50% percent of the population felt discomfort in 1990. Climate change affects the balance of exchange of energy between the environment and the human body which causes discomfort. DI indicates outdoor thermal comfort of the urbanities (Poupkou et al., 2011). Our findings on the trend and spatial variation of temperature in Figure 6 clearly show the increasing temperature due to urban heat island formation in the valley. Extreme heat events (EHEs) are anticipated to dramatically exacerbate the valley's already elevated temperatures by the end of the century (Meehl and Tebaldi, 2004). Extreme climatic conditions and air pollution magnifies the risk of mortality or morbidity, in the people of Kathmandu valley. The fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projects a significant increase in illness, death and discomfort due to negative impact of climate change and changes of ecology (Confalonieri et al., 2007). Thus, public health adaption to the climate change is emerging issue of concern.

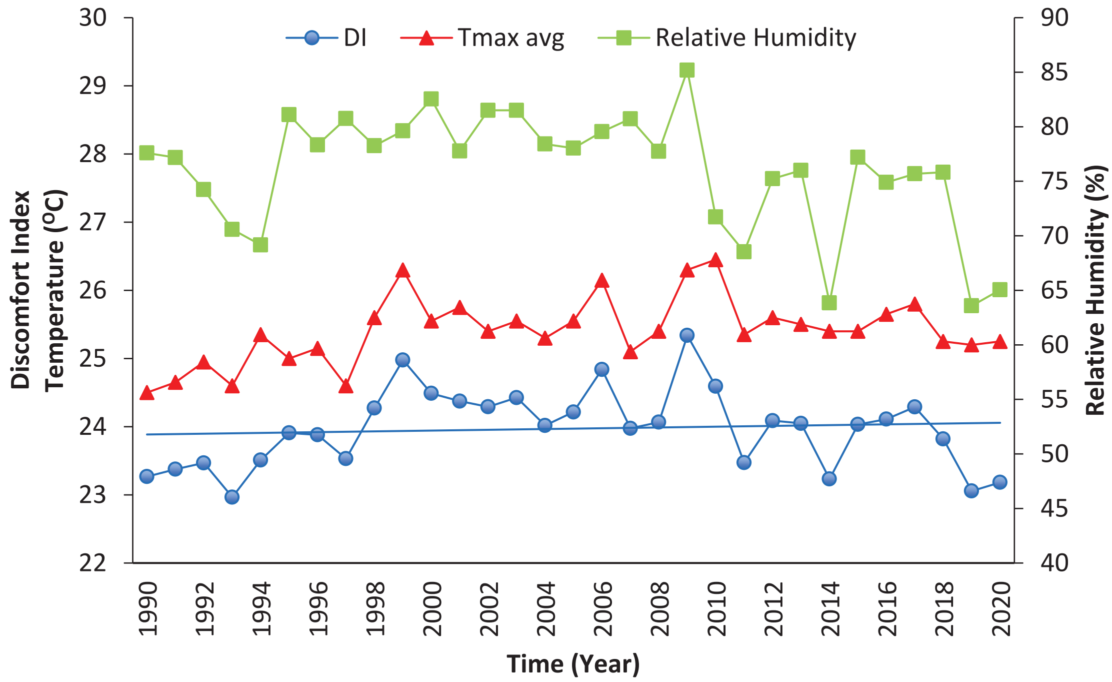

Figure 15. Change of Discomfort Index (DI) from 1990 to 2021

4. Mitigation Measures

The comparative analysis of land use of Kathmandu valley highly enlightens heavy growth in a built-up area between 1990 and 2021. Urbanization incorporates huge development of infrastructure which is inevitable due to the increasing population but it comes at a cost. A huge amount of Green House Gases (GHGs) is emitted from infrastructure construction, construction materials, and operation. The peripheral area of the valley has many brick kilns, a widely used material used in building construction in Kathmandu, which emit a high amount of GHGs and gets entrapped inside the bowl-shaped valley. The advancement of the living standard of urbanities encourages the use of various technologies for improving lifestyles. On the other hand, for the mitigation of the impact of urbanization, different policies, and technologies have been developed worldwide. Many developed and developing countries are aiming for fewer emissions and have adopted different policies including increasing the use of renewable energy, improving energy efficiency in buildings, and industry, and measures to reduce emissions from landfills and the like. Some of the widely used technologies, applicable to Kathmandu valley, are discussed below sections and as represented in Figure 14:

4.1 Low-Carbon Urban Infrastructure

Today, almost every major city in the world relies heavily on very energy-intensive urban infrastructure. According to the International Energy Agency (IEA) in 2008, cities will consume about 73% of the world's energy by 2030, causing a similar proportion of global GHG emissions (Lechtenbohmer et al., 2010). So, to reduce GHG emissions, urban infrastructure needs to move to systems with low energy consumption and near zero emissions by the middle of the century. For example, low-carbon buildings are designed to release very little or no carbon. Personal vehicle use is one of the major sources of carbon emissions, so urban mass transport (like metros) reduces personal vehicle usage and thus helps to substantially reduce carbon emissions.

According to the concept of low-carbon urban design, the shape of the city and the kind of buildings can be adjusted to meet reduced carbon emission criteria, which can alter the energy and carbon performance (Liu et al., 2016). For instance, from its initial association with stormwater management to a more comprehensive framework for sustainable urban water management, Australia's water-sensitive urban design has evolved. It provides a general and unified way to integrate the interactions between urban design (including landscapes) and the urban's water cycle. Some of the strategies adopted to mitigate GHG emissions during construction include: reducing the quantity and transportation distance of materials, using recycled materials, and recycling the demolition waste rather than dumping it in a landfill. Similarly, during the use of renewable energy, minimizing fuel energy consumption supports in reduction of carbon emissions.

4.2 Electric Vehicles

Pollution causes adverse environmental conditions which ultimately triggers the UHI phenomenon. Fossil fuel-operated vehicles cause high emissions of carbon which can be completely reduced with the introduction of an electric vehicle. Nepal has a high potential for hydroelectricity generation which is a clean source of electricity generation. Thus, this can be the most efficient mitigation paths for limiting global warming to 1.5 °C over the pre-industrial level. However, the use of electric vehicles is dominated in developed countries and developing countries like Nepal are also highly influenced. India, Indonesia, Thailand, and Bhutan which are developing countries in Southeast Asia, subsidies the tax on electric vehicles and also adopted different policies to promote the use of electric vehicles. Energy storage facilities can help to solve the problem of the imbalance between supply and demand for energy during peak hours.

4.3 Green Roof Technology

As the result suggests, the Kathmandu valley has turned into a concrete jungle with the reduction of green spaces. A green roof is simply a vegetated roof that is incorporated on top of buildings to compensate for the green spaces in order to curtail the UHI effects for restoring a healthy environment. Different studies have justified replacement of traditional roof surfaces with green roofs has helped lower temperatures in summer and intensify the thermal performance (Baniya et al., 2018; Li and Yeung, 2014; Magill et al., 2011; Xiao et al., 2014). The basic idea behind this mitigation scenario is either to reduce the solar radiation absorbed by the surface or to increase the radiation from the surface. Urban settings may have a limited amount of space, but it is still possible to incorporate small green infrastructure techniques into grassy or barren areas, vacant lots, and public rights-of-way.

4.4 Climate Change Management

For climate change management, Nepal had been performing actively since it became a party of the United Nations Framework Convention on Climate Change in 1994. To mitigate the effects and hazards of climate change, the nation has formulated several policies, such as the National Climate Change Policy (NCCP), 2019, and Nationally Determined contribution (NDC), 2020 (MoFE, 2019; MoFE, 2021). To reduce greenhouse gas emissions, Nepal’s National REDD Strategy has been formulated.

Studies show that global mitigation goals and the fight against climate change cannot be achieved without utilizing forests, reducing deforestation and forest degradation, and improving reforestation and forest management (IFM) (Federici et al., 2017; Grassi et al., 2017; Rockstrom et al., 2017). To limit within the 1.5 or 2.0°C range, carbon dioxide removal (CDR) needs to be increased where forest plays a huge role (IPCC, 2018). According to Le Quéré et al. (2018), changes in land use, such as the conversion of forests to agriculture, urban areas, and transportation routes, release about 1.3 GtC/yr annually (Le Quere et al., 2018). They have an impact on the biogeophysical processes that regulate the flow of energy and water between the land and the atmosphere. To combat climate change, reforestation could play a great role as it creates natural forests that are effective carbon sinks and can significantly reduce the amount of forest carbon loss due to unnecessary disturbances in the name of management (Law et al., 2018). However, worldwide forests and other land use (excluding agriculture) receive only 3% of the available world climate funds (Buchner et al., 2015).

Prioritizing forest management, implementing the existing laws and policies and awareness at the local level could play a great role in mitigating climate change. So, Kathmandu valley being prone to climate change impacts, the country should not only be focusing on mitigating options but also practice real and transformative adaptation.

5. Conclusions

Land use change in Kathmandu Valley is increasing rapidly. In 1990, the area of cultivated land was the highest, and in 2020,41.67% of Kathmandu valley is covered by urban/built-up. The rapid urbanization in Kathmandu is resulting in various environmental problems including the UHI effect. The comparison of temperature was done between Kathmandu Airport, Khumaltar, and Panipokhari as the urban core and Godavari as a rural area in order to obtain the magnitude of the UHI effect. The results of this study indicate that impacts of the UHI phenomenon can be experienced in Kathmandu and if no steps for mitigation are taken these impacts will grow in magnitude in nearby future. The mitigation strategies that can minimize the effect of UHI and the effectiveness of those strategies can be accurately analyzed through a suitable modeling system provided that detailed urban data is available. Similarly, analysis of spatial images discovers the reduction of vegetation which signifies degrading environmental conditions, and increment of land surface temperature leading to the urban heat island. Also, the UTFVI is found to be harmonizing strongly with the UHI phenomenon. The correlation between NDVI and LST is verified to be inversely related to each other. Furthermore, the Discomfort index and its analysis revealed that more than 50% percent of the population feels discomfort, and is an increasing trend since 2007. Urban warming in relation to global warming has a robust reaction to urban climate change and the public health of urbanites. Therefore, to confront these issues and curtail the ecological and health risks, the implementation of mitigation measures is of high priority. The evaluation of the UHI effect and its mitigation strategies have shown that the UHI effect is evident in the rapidly urbanizing city of Kathmandu. Still, there is a need of conducting more research for its proper assessment and implementation. Proper mitigation strategies must be implemented to minimize the effect of UHI. Increasing the area occupied by parks, planting plants, trees within the compound of houses and also by green roofing, and replacement of fuel-burning vehicles with electric vehicles are the most effective mitigation measure for Kathmandu Valley. Thus, the UHI effect must be considered by policymakers while dealing with urban infrastructure planning and management.

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Appendix:

Table 4. Thom's Discomfort Index (DI) and corresponding discomfort condition (Source: Thom, 1959)

Condition	DI index
No discomfort	<21
Under 50% of the population feels discomfort	21-24
Over 50% of the population feels discomfort	25-27
Most of the population feels discomfort	28-29
Everyone feels stress	30-32
State of a medical emergency	>32