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# Effects of rising urban temperatures on the wellbeing of the residents:

*A case study of Kolkata Metropolitan Region*

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**Key words**: Land Surface Temperature, Temperature Emissivity Separation, Ambient Air Temperature, Landuse, Stress Degree Days

**Abstract**: Urban climate changes and the warming of the cities are serious issues that cannot be overlooked. One of the most common inferences for these changes is unprecedented and unplanned urbanization, which further causes a rise in local, regional, and even global temperatures. Although the rate of urbanisation defines and greatly influences the city's socioeconomic worth and GDP per capita, if the urban expansion is hap-hazardous, it can cause serious environmental harm.There has been a steep rise in global urban population over the past three decades, and the highest growth rates have been observed in Asian and African cities. These two continents have been predicted to contribute to almost 90% of the total urban growth from the present to 2050. India is one of the few highly susceptible countries to the harsh effects of climate change in terms of rise in temperatures. After 1990s', India has observed substantial changes in the landscape due to urbanization, which has led to a significant rise in the surface and ambient air temperatures, further affecting the planet's health. Elevated temperature drastically affects the health of urban dwellers leading to a rise in stress and discomfort levels. Estimation of Land Surface Temperature (LST) can play a vital role in understanding the region-specific alterations in temperatures as it uses satellite data that captures the entire region and provides the information in the form of pixels. Traditionally, the temperature was measured at meteorological stations and extrapolated for the entire region,whichinduces inaccuracies. This ambiguity can be amended by developing a relationship between LST and ambient air temperature. This communication focuses on LST estimation using Radiative Transfer Equation algorithm corresponding to various Landuse categories. The study also attempts to create a relationship between the LST and the ambient air temperature observed at two meteorological stations. An overall assessment of the number of days under stress for the residents was also performed over several years. Kolkata Metropolitan Area was considered the study area to represent the results and understand the complete analysis. A rise of 6.77°C was observed in LST over the study period (2000 -2019) due to an increment of 200% in the urban area. Analysis of the number of days under stress showed an increasing trend for the study area due to alterations in urban temperatures. These results and the suggestions from the scientific community, urban planners, and climate experts will help develop or modify the current policy frameworks for creating a balance between development and the environment, thus creating sustainable urban development.

# 1. INTRODUCTION

Humans have delivered a massive revolution in all fields from the dawn of history, thanks to their vast knowledge and wisdom. However, humans have developed a mindset that they are superior to all other living beings and continue to abuse nature for resources to obtain immediate benefits. Initially, this exploitation was unnoticed owing to minor or negligible alterations that could be accepted; however, it gradually began impacting the climate locally and further progressed to regional and global levels(Karoly, Braganza et al., 2003; Keeling, 1997; Stott, Mitchell et al., 2006). Climate change has become one of the most challenging issues in recent decades, attracting the attention of the global scientific community. It is no longer an environmental concern, instead is one of humanity's greatest developmental challenges. One of the most significant aspects of these changes is rising demographic pressure as a consequence of individuals migrating to cities in search of a higher standard of living and a better quality of life, resulting in unplanned and hap-hazardous urbanization. Augmented growth in terms of intensity and extent leads to disjointed urban development that contributes to inadvertent urbanization, resulting in extensive landuse changes, causing the majority of the global cities to expand beyond their municipal and administrative boundaries.

As a result, the amount of waste generated increases, posing a waste management concern (one of the most common problems in cities). Additionally, to meet the energy demands of the urban population, power plants have toconsume more energy sources, which results in a larger discharge of pollutants into the atmosphere, increasing the levels of GHGs (greenhouse gases), SPMs (suspended particulate materials), and PMs (particulate matters). Larger the urbanized area, higher is the vehicular count, resulting in traffic congestion that not only deteriorates the resources (fuel) but also pollutes the air. A rise in the concentration of GHGs and PMs alters the atmospheric reactions/processes, causing global warming (Ramachandra, Aithal et al., 2015). Furthermore, urbanization influences the region's biodiversity,sincethe flora and fauna cannot acclimatize to the changes and eventually migrate or die. To house the increasing urban population, the landscape of the region changes, which can be understood by landuse/landcover (LULC) alterations.

LULC changes occur in the form of converting vegetated spaces, agricultural lands, and open spaces into urban pockets (Chandrashekar and Aithal, 2021; Kandlikar and Sagar, 1999; Mallick, Kant et al., 2008; Ramachandra, Aithal et al., 2016), which affects the rate of evaporation, surface albedo, storage of heat, moisture content of the soil, wind turbulence and solar radiation (Pal and Ziaul, 2017).All of these have a profound effect on the city's environmental factors and living conditions, such as thermal comfort, air temperature, and land surface temperature. Land surface temperature (LST) can be referred to as the radiative skin temperature of the earth's surface (Ministry of Statistics and Programme Implementation, 2015). It plays a crucial role in determining the energy balance and climate change in terms of global warming and the greenhouse effect. It determines the earth's surface's effective blistering temperature and influences energy exchange, biogeochemical cycle, crop and wind patterns, rainfall, biodiversity, and ecology (Bharath, Rajan et al., 2013; Jin, Li et al., 2015; Nimish, Chandan et al., 2018). Estimation of LST depends upon surface albedo, moisture content in soil and atmosphere, health and density of vegetation, surface characteristics, season-of-year, and time-of-day. Optimal power generation to meet residents' demands is escalating the concentration of pollutants in the atmosphere in the form of particulate matter ($PM_{10}$, $PM_{2.5}$, $PM_1$ and Suspended PM) and Greenhouse Gas such as $CO_2$, CO, $NO_X$, $SO_X$, $O_3$, $CH_4$, etc. These alterationssourcesa rise in LST, resulting in the formation of urban heat islands (Anderson, Norman et al., 2008; Khandelwal, Goyal et al., 2018; Li, Z.-L. and Becker, 1993; Li, Z.-L., Tang et al., 2013; Ramachandra, Bajpai et al., 2017; Running, Justice et al., 1994; Schmugge and Becker, 1991).

Increased LST gives rise to heatwaves, which are considered a serious menace to all living beings. Urban areas, due to the effect of urban heat islands (UHI) and large population density, are highly vulnerable to these heatwaves(Misni, Baird et al., 2013).Heatwaves have become a frequent phenomenon in recent yearsas a result ofthe growing UHI effect and are getting stronger for longer periods, aggravating the problem of thermal danger for local inhabitants (Founda and Santamouris, 2017; Mouada, Zemmouri et al., 2019). UHI is the major phenomenon that is observed in large cities, where the temperature of the core city becomes more when compared to its natural surroundings (Liang and Shi, 2009). Numerous sources instigate UHI, but the most significant one is the modification in the surface energy budget, i.e., the variation in the heat storage/retention capacity of surfaces, which affect the latent and sensible heat budget as well as the advective and convective energy flow (Oke, 1982; Roth, 2012). Compared to any naturally existing surface (vegetation, waterbody, moist soil) and building materials utilised in rural regions, paved surfaces in cities have a lower albedo, which lowers the evapotranspiration, allowing more heat to enter the atmosphere in urban areas. The canyon-like structure of tall buildings and rough-structured constructions prevents solar energy from escaping; instead, the heat is trapped due to multiple reflections, resulting in reduced infrared heat losses. Increased pollution from automobiles and industries leads to higher temperatures due to reduced radiative cooling (King and Davis, 2007; Liang and Shi, 2009). Numerous scientific studies suggest that there will be a high rise in the number of people who will be exposed to extreme weather events due to alterations in surface temperatures. Elevated LST can affect the quality of life in multiple ways – power outage, deterioration in air quality, poor health, thermal discomfort, food, and water crisis, rise in extreme events and disasters, increased mortality rates.

India is one of the few countries vulnerable to climate change due to its large population depending on the agrarian economy, coastal areas, Himalayan region, and islands. India faces several climate extremes every year, causing several deaths. The crucial environmental challenges in India have been sharper over the last two decades as climate change is affecting the natural ecosystem, creating food and water security problems. All of these issues need an LST-based visualisation and evaluation of urban microclimaticalterations. This communication establishes a link between changing landscape and LST, which can assist decision-makers in improving existing policies and developing new ones for future sustainable development in terms of infrastructure, basic amenities, food, freshwater availability, solid waste management, and health (Nimish, Chandan et al., 2018). The study also determined the number of days a normal human being would be stressed because of temperature being above or below the human comfort levels.

## 2. LITERATURE REVIEW

Several scientific literatures have inferred a direct relationship of urbanization with the economy and sustenance but on the contrary, if it is not planned properly, it can severely affect the living conditions and health of the city (Chen, Zhang et al., 2014; Chenery and Taylor, 1968; Henderson, 2003). Rapid and unplanned urbanization is associated with several impacts such as increased LST and altered natural environment (Guo, Wang et al., 2012), shortage of housing facilities (Petkar, Macwan et al., 2012), loss of native ecosystem, forests and green spaces (Pauchard, Aguayo et al., 2006), destroyed ecosystem for aquatic species (Gillies, Box et al., 2003), reduction of the groundwater level and its quality (Graniel, Morris et al., 1999), poor health and spread of diseases (Mapping health, 2018; Mehrotra, Bardhan et al., 2018; Ooi and Phua, 2007), and traffic congestions (Mitsubishi Corporation, 2018). Landuse and Land cover play an important role in defining the terrestrial climate and environment in anthropogenic and natural related terms. Alteration in LULC is directly correlated with micro-, meso- and macro-climate change and global warming (Mahmood, Pielke Sr et al., 2010). Fatemi and Narangifard (2019) investigated LULC changes over Shiraz city and inferred reduction in vegetation as the main consequence of rising LST. Derdouri, Wang et al. (2021) analysed several case studies conducted between 2001 to 2020 to identify a significant rise in SUHI (surface urban heat island) owing to the modifications in the landuse of the cities. Several other studiesreported a close relationship between landscape modification in terms of increased impervious urban surfaces (on the cost of blue-green infrastructure) and rising LST over the cities across the globe (Adeyeri, Akinsanola et al., 2017; Ahmed, Kamruzzaman et al., 2013; Chandra, Sharma et al., 2018; Daramola, Eresanya et al., 2018; Hale, Gallo et al., 2006; Huang and Lin, 2013; Imran, Hossain et al., 2021; Jun, Kim et al., 2017; Kottmeier, Biegert et al., 2007; Lu, Yue et al., 2021; Pal and Ziaul, 2017; Rehman, Qin et al., 2022; Tran, Pla et al., 2017). Heatwaves are triggered by these changes in urban landscape pattern and LST, which further exacerbates the phenomena of urban heat island (UHI). Scientists from around the world are seeking to comprehend urban climatology, keeping an emphasis on perceiving and detailing the phenomenon of Urban Heat Islands (UHI) in cities (Stewart, 2011). All these studies and other scientific literature necessitate a continual visualization and monitoring of the landscape and LST.

The landscape and LST changes can be detailed out by developing several relationships and indices. These relationships and indices are capable of providing deeper insights into the region’s microclimatic changes. In usual scenarios, temperature is extremely sensitive to even little changes in the region’s landscape and climate, and it alters drastically with a change in any one of those. On the other hand, LST measures the surface temperatures at the pixel level with fine/coarse resolutions and can detect any abrupt and even minimal changes (Valiente, Niclòs et al., 2010). Therefore, deriving a relationship between LST and ambient air temperature would be highly valuable in minimizing/eliminating the problem of inaccuracies. do Nascimento, Galvani et al. (2022), compared the air temperature and LST for the city of Sao Paulo and observed a mean difference of 1.2 – 1.9°C in spring-summer seasons and 5.8 – 11.5°C in winter-autumn season. Kawashima, Ishida et al. (2000), developed a relationship between air temperature and land surface temperature for point data and the vicinity. Another analysis by Shen and Leptoukh (2011) estimated a relationship between LST and ambient temperature for day and night time. Mutiibwa, Strachan et al. (2015), linked air temperature and LST for a complex terrain and observed that the parameter had a significant association throughout late summer and fall, but a poor relationship during the winters and early spring. Sun, Sun et al. (2020) estimated UHI with LST and near surface air temperature and observed a good consistency. The growing demand and widespread mobility of people in urban areas is severely impacting the residents'wellbeing, necessitatingan immediate need for a planned urban growth with implementation of stringent policies and measures.

# 3. METHODOLOGY

## 3.1 Study Area

Kolkata Metropolitan Area (KMA), as shown in *Figure 1*, one of India's largest metropolitans, was chosen for analysis based on infrastructure (planned and unplanned), level of urbanization, socio-economic variables and population. To investigate the variations in temperature due to urban sprawl and conduct an urban heat island (UHI) analysis, a 10 km buffer surrounding the metropolis was considered. Kolkata, often known as the "City of Joy", was the first capital of British India and is known for its historical significance as well as its high-tech lifestyle. It is an important hub for art, literature, cultural heritage, and architecture. However, the metropolitan area is currently experiencing issues such as rising pollution as a consequence of landuse changes, building activity, and traffic congestion as a result of increasing demographic pressure. The amount of RSPM (respirable suspended particulate matter) has soared in the region, resulting in deteriorated air quality and an increase in respiratory diseases such as asthma and lung cancer. These changes have resulted in a slew of environmental issues, and the city is experiencing microclimate change, leading to higher LST and heatwaves. The geographic and demographic information about the study area is shown in *Table 1*.

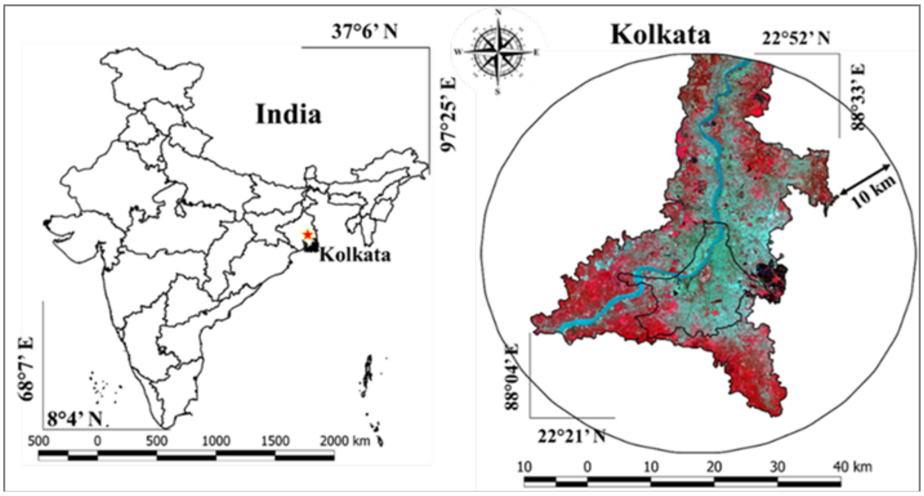


*Figure 1.* Study area

*Table 1.* Geographic and demographic profile: KMA

| | | | |
|---|---|---|---|
| **Area** | 1886.67 km$^2$ | | |
| **Latitude** | 22˚ 34' 21" N | | |
| **Longitude** | 88˚ 21' 31" E | | |
| **Altitude** | 1.5 – 9m above mean sea level (1% drainage gradient) | | |
| **Mean annual rainfall** | 185 cm/year | | |
| **Climate** | AW category (according to Koppen's climate classification) – tropical wet and dry climate | | |
| **Temperature** | Winter minimum (Nov – Jan): 12ºC to 23ºC<br>Summer maximum (April – July): 27ºC to 38ºC | | |
| **Population** | **Year** | **Population** | **Decadal growth rate (%)** |
| | 1971 | 7,420,000 | - |
| | 1981 | 9,030,000 | 21.70 |
| | 1991 | 10,890,000 | 20.60 |
| | 2001 | 13,217,000 | 21.37 |
| | 2011 | 14,112,536 | 6.78 |
| **Population density (as of 2011)** | ~3879 people per sq. km. | | |

## 3.2 Data

Primary and secondary data necessary for the analysis were acquired as shown in *Table 2*, and *Table 3* lists the satellite, sensor, and date of data acquisition.

*Table 2.* Geographic and demographic profile: KMA

| | |
|---|---|
| **Primary Data** | Field data for validation |
| **Secondary Data** | • Landsat series (5: Thematic Mapper, 7: Enhanced Thematic Mapper + and 8: Operational Land Imager/ Thermal Infrared Sensor)<br>• City Development Plan<br>• Survey of India Toposheets (1:50,000, 1:250,000)<br>• Google Earth Pro<br>• Indian Meteorological Department (IMD) |

*Table 3.* Data Acquired – Satellite, Sensor, and Date

| S. No. | Satellite | Sensor | Date |
|---|---|---|---|
| 1. | Landsat 5 | Thematic Mapper | • February 11, 2000<br>• March 25, 2004<br>• March 07, 2009 |
| 2. | Landsat 8 | Operational Land Imager/ Thermal Infrared Sensor | • March 21, 2014<br>• May 06, 2019 |

The raw images captured from the satellite were pre-processed to rectify the errors induced due to the satellite's motion, atmospheric elements such as trace gases, particles, and water vapour. The data was geo-corrected using the GCPs (ground control points) acquired via ground sampling and Google Earth. For further analysis, the data was clipped concerning the area of interest.

## 3.3 Method

*Figure 2* depicts the entire method followed for the analysis and is detailed further below.

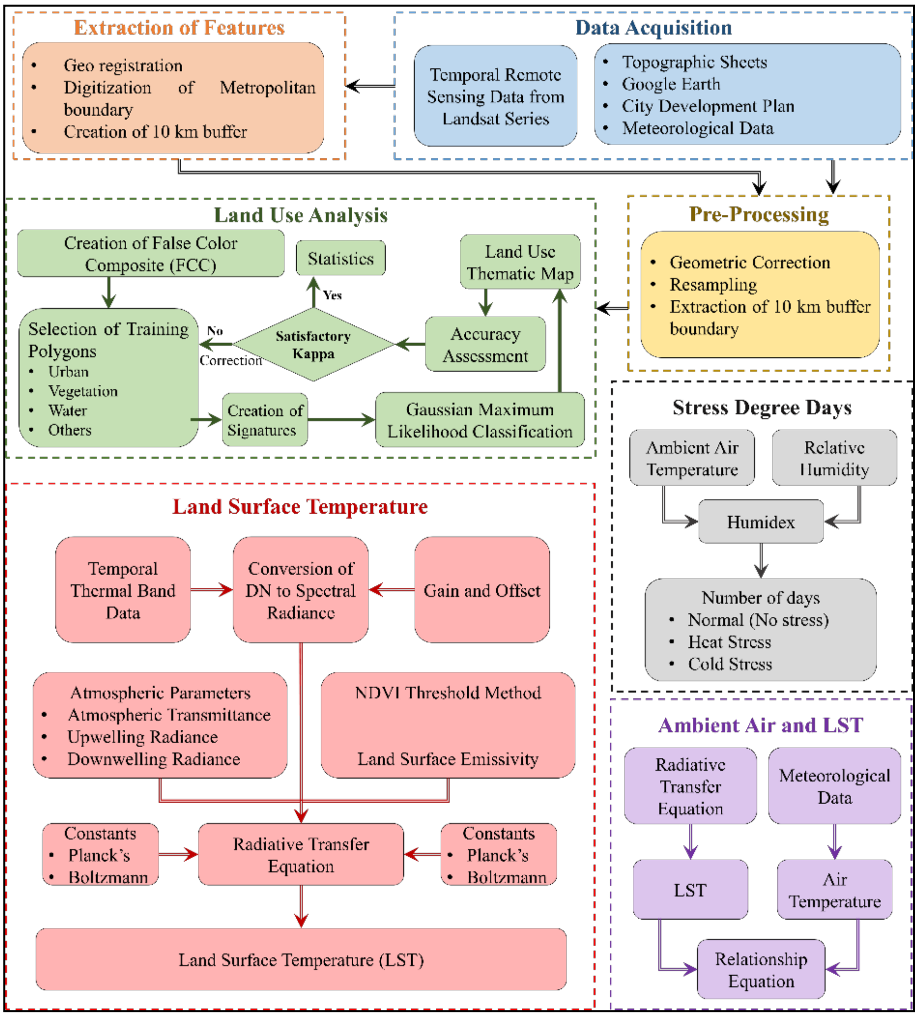


*Figure 2.* Method used in the analysis

### 3.3.1 Land use analysis

Landscape analysis was carried out by developing a landuse map for the study region. By assigning blue, green, and red colours to the green band, red band, and NIR band, respectively, a false colour composite (FCC) was created (Ramachandra, Aithal et al., 2016). The composite's heterogeneity was then utilised to digitise polygons that defined each class's representative sample. The FCC was used to create signatures for these polygons by assigning mean and covariance values. Based on the signatures that serve as input, a supervised classification approach called Gaussian Maximum Likelihood Classification (GMLC) was used to categorize the whole study area into four classes (*Table 4*). GMLC is one of the most extensively used algorithms since it offers high accuracy classification (Joevivek and Chandrasekar, 2010). It classifies the scene using probability density functions and is regarded as one of the most accurate algorithms for landuse classification. The accuracy of the classification was calculated by estimating the overall accuracy and kappa coefficient using the confusion/error matrix (Lillesand, Kiefer et al., 2015). GMLC can be mathematically expressed as:

$$X \in C_j, \text{ if } p(C_j/X) = \max[p(C_1/X), p(C_2/X), \ldots, p(C_m/X)] \quad (1)$$

Here, $p(C_i/X)$ denotes the conditional probability of pixel X being a member of the class; max $[p(C_1/X), p(C_2/X), \ldots, p(C_m/X)]$ is a function that returns the largest probability among four categories

*Table 4.* Data Acquired – Satellite, Sensor, and Date

| Landuse Class | Features included in the class |
|---|---|
| Urban | Impervious/Paved surfaces including residential and industrial buildings, mixed pixels containing more than 50% built-up |
| Vegetation | All the vegetated areas including forests, gardens, parks, nurseries, sown agricultural fields, etc. |
| Water | Lakes, Ponds, Tanks, Reservoirs, Aquaculture |
| Others | Barren agricultural fields, open grounds, rocks, mining areas, unconstructed roads, etc. |

### 3.3.2 Estimation of Land Surface Temperature

The thermal band of the electromagnetic spectrum, ranging from 10.4 to 12.5 m, can be utilised to capture the surface temperatures of objects on the Earth's surface in remotely acquired data. Each data pixel is represented by DN (digital numbers), which is equivalent to the amount of energy reflected to the sensor. When these values along with the atmospheric parameters and emissivity from the features, are fed to the algorithms, the surface temperature can be measured. This communication uses Radiative Transfer Equation (RTE) to estimate LST over the study area, since the algorithm considers atmospheric parameters such as transmittance and upwelling-, downwelling-radiances.

*Atmospheric Parameters:* The Atmospheric Correction Parameter Calculator (https://atmcorr.gsfc.nasa.gov/) was used to compute parameters such as atmospheric transmittance, upwelling, and downwelling radiation. It considers information such as the year, month, day, time, and geographic coordinates of the scene captured. Weather variables such as altitude, pressure, air temperature, and relative humidity can be specified as an option.

*Land Surface Emissivity:* The NDVI (Normalized Difference Vegetation Index) threshold approach was applied to quantify land surface emissivity,whichserves as an essential element for estimating LST. The emissivity values for pure pixels of water, soil, and vegetation are separated in this technique, and mixed pixels (soil and vegetation) are evaluated based on the proportion of vegetation. A comprehensive literature review revealed that the emissivity values for pure soil, water, and vegetation were 0.9668, 0.9910, and 0.9863, respectively (Sekertekin and Bonafoni, 2020; Yu, Guo et al., 2014). Equation 2 was used to calculate emissivity for mixed pixels (Sobrino and Raissouni, 2000; Nimish et al., 2020).

$$\varepsilon_{SV} = \varepsilon_V P_V + \varepsilon_S(1 - P_V) + C \quad (2)$$

Here, $\varepsilon_{SV}$ is the emissivity of soil+vegetation; $\varepsilon_V$ is the emissivity of vegetation; $\varepsilon_S$ is the emissivity of soil; PV is the proportion of vegetation; C is a constant that defines surface characteristics.

*Land Surface Temperature:* To estimate LST, the above-mentioned parameters and raw satellite images were provided as input in a simplified RTE, as shown in Equations 3 to 6.

$$B_i(T_i) = \tau_i[\varepsilon_i B_i(T_s) + (1-\varepsilon_i)I_i^{\downarrow}] + I_i^{\uparrow} \quad (3)$$

Here, $B_i(T_i)$ is the top-of-atmosphere radiance received at the sensor for channel I having $T_i$ at-satellite brightness temperature; $\tau_i$ is atmospheric transmittance for channel i; $\varepsilon_i$ is emissivity for channel i; $I_i^{\downarrow}$ is downwelling radiance; $I_i^{\uparrow}$ is upwelling radiance.

$$B_i(T_s) = (Gain*DN) + Offset \quad (4)$$

Here, $B_i(T_s)$ is ground radiance; Gain is the band-specific multiplicative factor; Offset is the band-specific additive factor.

$$B_i(T_s) = \frac{2hc^2}{\lambda_i^5 \times \left(e^{\frac{hc}{\lambda_i k T_s}} - 1\right)} \quad (5)$$

Here, h is Planck's constant ($6.626 \times 10^{-34}$ J-s); c is the speed of light ($2.98 \times 10^{8}$ m/s); $\lambda_I$ is the effective wavelength for channel I; k is Boltzmann constant ($1.3806 \times 10^{-23}$ J/K); $T_s$ is Land Surface Temperature

$B_i(T_s)$ was estimated using Equation 4 and $T_s$ was estimatedusing equation 6,whichis formulated by rearranging Equation3 and 5 and putting the value of constants.

$$T_s = \frac{C_1}{\lambda_i \times \ln\left(\frac{C_2}{\lambda_i^5\left(\frac{B_i(T_i) - I_i^{\uparrow} - \tau_i(1-\varepsilon_i)I_i^{\downarrow}}{\tau_i \varepsilon_i}\right)}\right)} \quad (6)$$

Here, $C_1 = 14387.7$μm-K; $C_2 = 1.19104 \times 10^{8}$ W-μm$^4$-m$^{-2}$-sr$^{-1}$

# 4. RESULTS AND DISCUSSION

## 4.1 Landuse analysis

Over the study period, 2000 to 2019, a comprehensive temporal landscape analysis in the form of landuse was performed for the KMA area and 10 km buffer. *Figure 3a* and *3b* show the landuse maps and the percentage contribution from each landuse category. The accuracy assessment fetched an overall accuracy varying from 94.33% to 95.67% with kappa coefficient ranging from 0.90 to 0.93. During the study period, the metropolitan's urban area grew thrice, from 235.11 km$^2$ to 704.03 km$^2$, with infill (core) and dispersed (buffer) types of urban expansion. The metropolitan area has seen urban sprawl in all directions, particularly to the north and northeast. Due to the inclusion of agricultural fields that might be sown or unsown at the image collection time, small undulations were observed in the vegetation and others category during the analysis. The water bodies in the region have seen a rise from 3.09% to 4.37% due to an increase in wetlands and aquaculture towards the eastern part of KMA.

Kolkata, India's third-biggest urban agglomeration, is one of the country's oldest and largest metropolitan areas. Currently, the metropolitan area is home to about 16 million people, with two-thirds of the population living in sprawled suburbs. Continual growth in the metropolitan population has resulted in numerous landscape changes. The results indicate that the study area's core part became densely concretized. The urban areas to the north including Barrackpore, Chandannagar, and Panihati, as well as North Dumdum, Rajarhat, and Newtown in the north-eastern part of the study area have grown significantly. The development of different private and public sector industries, the establishment of headquarters for various multinational brands/companies, and the expansion of the information technology sector in the metropolitan region are just a few of the many causative variables connected with this growth. Due to the migration of government offices and upcoming industries between Andul and Biparnna Para, a sharp increase in urban areas were noticed on the western bank of the Hooghly River.

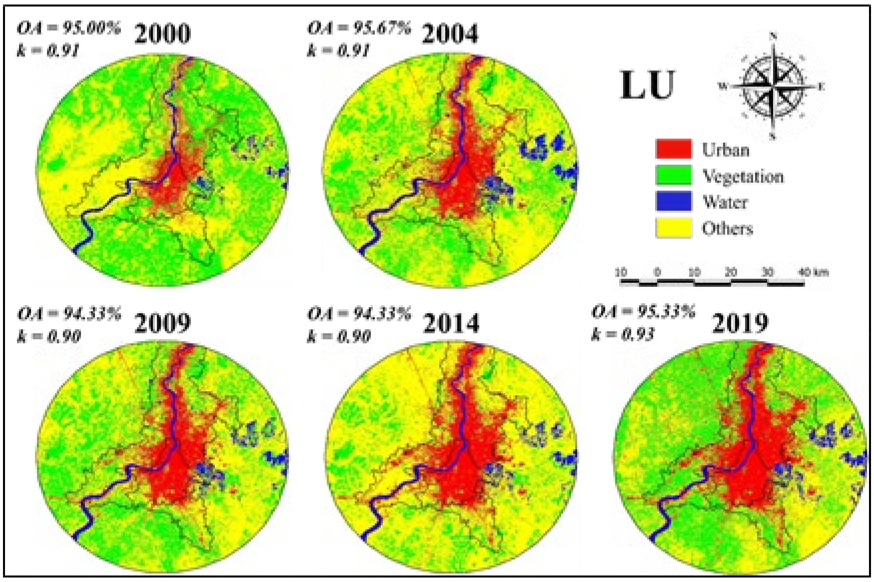


*Figure 3a.* Landuse maps for the study area

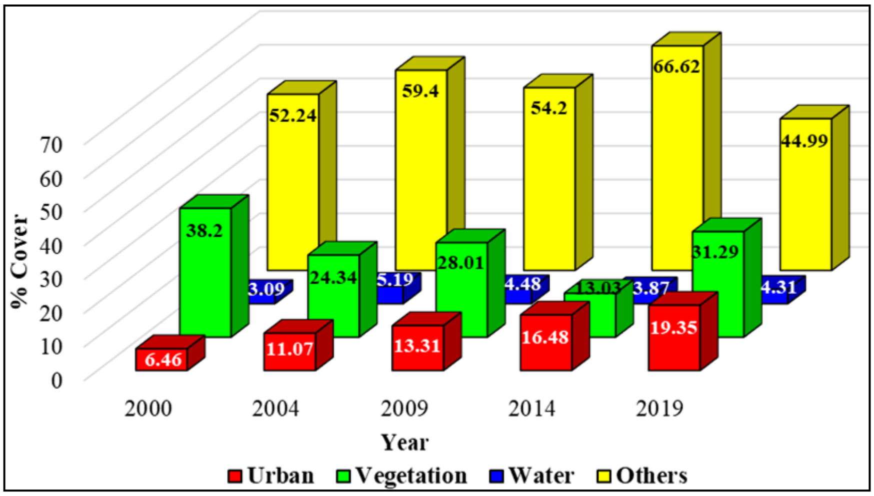


*Figure 3b.* Percentage covered by each land use class for the study area

## 4.2 Land Surface Temperature analysis

Temporal LST was estimated over the study area for 2000, 2004, 2009, 2014 and 2019, and the observations are shown in *Figure 4*. It was observed that the mean surface temperature of the region has increased from 22.97°C to 29.74°C. The region's minimum temperature has increased from 12.50°C to 24.35°C, while the maximum temperature has risen by 7.44°C. A class-wise analysis was carried out to better understand LST variability with landscape alterations and the outcomes are illustrated in *Table 5*. It was detected that the mean LST of the urban class had escalated by 6.37°C. The temperature of the vegetation and other classes has risen from 22.48°C to 29.43°C and 23.16°C to 29.44°C, respectively. The mean LST for the water bodies has increased by 6.16°C from 2000 to 2019.

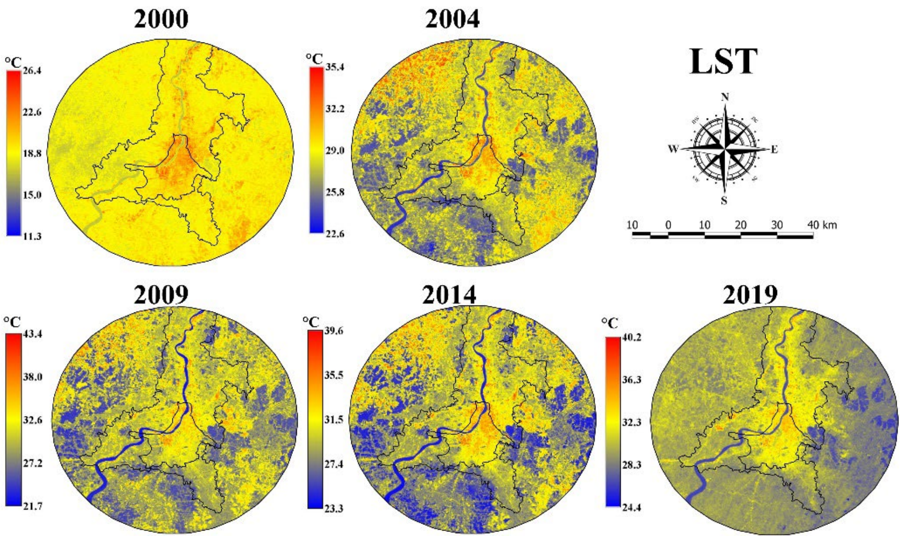


*Figure 4.* Land Surface Temperature maps for the study area

*Table 5.* Statistical description of LST for the study area

| | Mean LST (°C) | | | | |
|---|---|---|---|---|---|
| | **2000** | **2004** | **2009** | **2014** | **2019** |
| **Urban** | 25.16±1.56 | 29.23±1.39 | 31.89±2.29 | 31.17±1.93 | 31.53±1.46 |
| **Vegetation** | 22.48±0.70 | 26.34±1.06 | 27.41±1.82 | 26.18±1.39 | 29.43±0.73 |
| **Water** | 21.04±1.24 | 25.49±1.36 | 25.71±2.29 | 25.32±1.35 | 27.20±0.80 |
| **Others** | 23.16±1.04 | 28.22±1.48 | 30.54±2.19 | 29.25±2.02 | 29.44±0.98 |
| **Mean** | 22.97±1.22 | 27.74±1.73 | 29.63±2.77 | 29.01±2.46 | 29.74±1.42 |

Landuse analysis signified significant landscape alterations since the beginning of the study period, which has resulted in changes in the incoming and outgoing solar radiation leading to a significant rise in the land surface temperatures. The highest surge in LST was observed during the transition from 2000 – 2004, as the population inflow was at its peak during this period. As a consequence of saturation in the availability of land for construction, all the subsequent transitions have witnessed a declining trend in the rate of population growth, with 2009 – 2019 being minimal. LST and heatwaves largely depend upon the type of material, urban growth rate, and available vegetated and open spaces to dissipate the excessive heat and provide ample air movement and pollution dispersions in the urban spaces. Due to the lack of these breathing spaces in the city's core, urban areas in the city centre corresponded to the highest surface temperatures. Other areas such as Netaji Subhas Chandra Bose International Airport, Belur math, Ghusuri, Park Street, Taltala, Sealdah also signified high surface temperatures due to heavy movement of traffic and increased emissions.

Several industries and manufacturing units adjacent to the river Hooghly also showed a high temperature due to the type of roofing and construction materials used. The main factors contributing to the study area's high temperature are insufficient green and open spaces, densely packed urban structures, and high population load. The presence of river Hooghly within the study area, on the other hand, enhance the microclimate of the neighbouring spaces up to an extent but fails to reduce the soring LST for the entire metropolitan (Deng, Wang et al., 2018; Estoque, Murayama et al., 2017; Feizizadeh and Blaschke, 2013; Pal and Ziaul, 2017).

## 4.3 Relationship and index

### a) Relationship between LST and Ambient Air Temperature

On a daily basis, meteorological stations collect a substantial quantity of data about ambient air temperature; however, this data is in points. Since most climate models and algorithms require spatially distributed data, point data from Met stations are interpolated/extrapolated for the entire region, resulting in substantial errors (Daly, Halbleib et al., 2008). On the other hand, LST measures surface temperature at the pixel level and can detect even minor and sudden temperature changes. As a result, a relationship between LST and ambient air temperature can be considered quite valuable in understanding the region's thermal behaviour.

For this analysis, the ambient air temperature for the study period was acquired from IMD and online sources (https://www.wunderground.com). Cloud-free remotely sensed Landsat data was obtained for a similar time period, and LST was calculated using RTE. The chosen weather monitoring station'' geographical locations (Dum Dum airport and Behala airport) were noted, and the LST value of the associated pixel was compared to the ambient air temperature value obtained from the Met station. The data was linearly as well as non-linearly related using regression analysis to obtain the coefficient of determination ($R^2$).

The ambient air temperature measured at each Met station was correlated to the LST both individually and as a group. Linear and non-linear curve fitting were used with different polynomial degrees until the optimum coefficient of determination was achieved. *Figure 5*to*7* show the scatter plot with the final $R^2$ values. The air temperature data points obtained from the MET station at Dum Dum airport gave a reasonable match with an $R^2$ value of 0.63. With an $R^2$ value of 0.71, the temperature data points acquired from the Behala airport MET station showed a good fit. The LST value was higher because the Dum Dum airport is dominated by urban structures with high heat retention capacity; while there is a drop in ambient air temperature owing to the presence of wind draughts. Behala station, on the other hand, had a stronger relationship due to the dominance of green spaces and a lower proportion of urban structures. Due to LST and air temperature dependence on the kind of landuse class present at the Met station, $R^2$ was substantially decreased when the combined analysis was performed.

- **Dum Dum Met Station**

Air Temperature = $- 0.02 \times LST^2 + 2.15 \times LST -- 21.79$

$R^2 = 0.63$

Example: If, LST = 35ºC, then, Air Temperature = 29.50 ºC

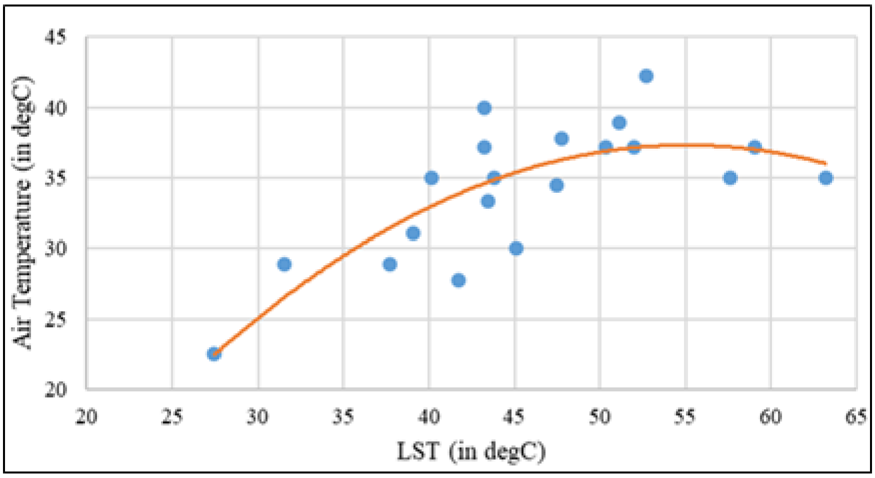


*Figure 5.* Scatter plot between LST and Air Temperature observed at Dum Dum MET station

- **Behala Met Station**

Air Temperature = - 0.04×LST$^2$ + 3.73×LST–- 42.21
$R^2$ = 0.71
Example: If, LST = 35ºC, then, Air Temperature = 34.90 ºC

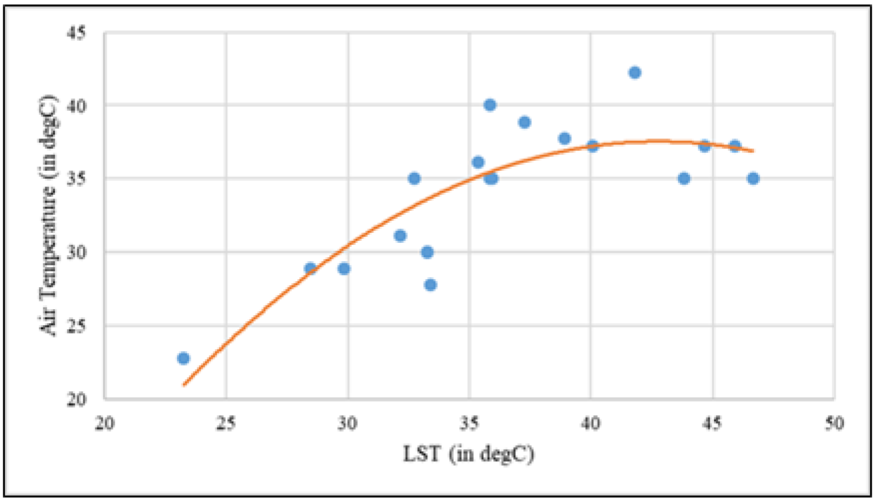


*Figure 6.* Scatter plot between LST and Air Temperature observed at Behala MET station

- **Combined data of both the Met Station**

Air Temperature = - 0.02×LST$^2$ + 1.93×LST–- 11.70
$R^2$ = 0.51
Example: If, LST = 35ºC, then, Air Temperature = 32.62ºC

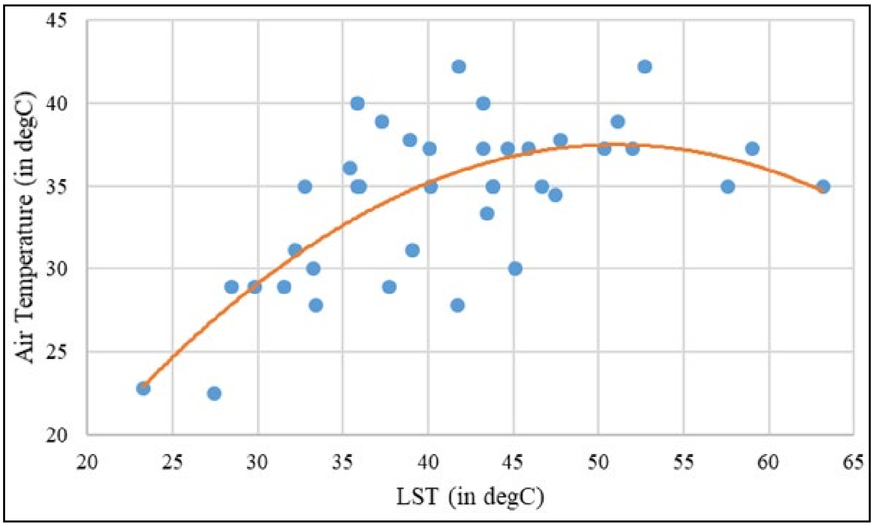


*Figure 7.* Scatter plot between LST and Air Temperature observed for combined data of MET station

## b) Stress Degree Days

Stress degree days (SDD) can be defined as the number of days on which an average person will be stressed due to elevated or reduced temperatures (Kirkham, 2014). It can be estimated by subtracting the air temperature by the threshold temperatures (~24-34°C for this study). A negative value signifies cold stress, while a positive value relates to heat stress (Helyes et al., 2006). A normal human being can efficiently work and reside in a temperature range that is suitable for their body, however, when the temperature reduces or increases beyond these thresholds, the capacity of working reduces and they feel stressed in terms of mental and physical wellbeing.This indicator is generally described concerning plant growth to determine if they are stressed. Humans may use a similar idea to determine which days are the most productive, have the highest thermal comfort, and have the least amount of climate-related stress.

From2001 to 2018, meteorological parameters including ambient air temperature and relative humidity were obtained from IMD and other internet sources (https://www.wunderground.com). Since temperature alone cannot adequately describe human thermal comfort, humidex was calculated as described in Equation 7, which considers the combined effects of temperature and humidity. The humidex values between 24ºC and 34ºC were considered thermally acceptable for the residents, as per the literature review (Błażejczyk et al., 2013) and understanding of the Indian sub-continent, particularly Kolkata (people in the study area are more prone to higher temperatures, as they have over the period of time acclimatized to the weather conditions). Any day with a humidex value outside of this range was regarded as stressful.However, it may be noted that the residents are not much impacted by cold degree daysand the study primarily focuses on the heat related stress.

$$Humidex = -42.38 + 2.05\times T + 10.14\times RH - 0.22\times T\times RH - 0.006\times T^2 - 0.05\times RH^2 + 0.001\times T^2\times RH + 0.0008\times T\times RH^2 - 0.000002\times T^2\times RH^2 \quad (7)$$

Here, T is ambient air temperature (ºF); RH is relative humidity (%)

The average daily humidex was calculated and divided into three categories: normal day (24ºC humidex 34ºC), heat stress (Humidex > 34ºC), and cold stress (Humidex 24ºC).These were then summed up for the entire year, and a plot was created, as shown in *Figure 8*. A rising trend was observed for the number of heat stress days; on the other hand, cold degree days showed a slight decrement. The number of days without stress was identified to have a linear trend with ups and downs over the study period. These variations can be attributed to large-scale changes in the region's surface temperatures due to greater landscape modifications to accommodate the region's burgeoning population.

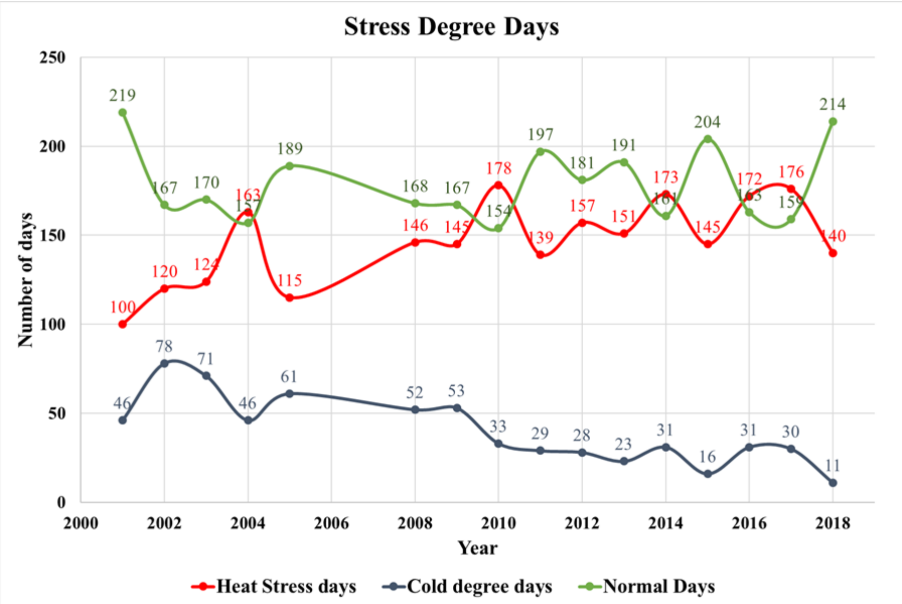


*Figure 8.* Stress Degree Days for Kolkata during 2001 to 2018

## 5. CONCLUSION

The research investigated the landscape changes in the form of landuse analysis for the Kolkata Metropolitan area over 19 years and explored its impact on the land surface temperature using the Landsat data. The study set out to estimate stress degree days and derived a relationship between ambient air temperature and LST for better understanding the thermal profile of the metropolitan. The main agenda of the study was to provide a clear picture of changing microclimate in the form of LST due to landscape alterations in an urban area to the urban developers, government bodies, and decision-makers. The research reveals a threefold increase in the urban area over the study area in 19 years, resulting in a 6.77ºC rise in LST. The relationship developed between ambient air temperature and LST provided a reasonably good relationship. Estimation of stress degree days offered an idea about an increment in the number of days on which a typical human is under stress due to heat which affects their productivity. This study indicates that a dense expansion of urban structures with little vegetation and open space can significantly influence the microclimate of the region, resulting in heat-related concerns for residents.

The important outcome of the study is that alteration in the urban landscape in the form of concrete impervious structures can result in increased surface temperatures. In general, concentrated and unplanned urban growth with reduction in the blue-green infrastructure (water bodies and vegetation) can contribute to city warming and severely impacts the residents in terms of heat-related stress (Li, Y. and Song, 2019). It is suggested to incorporate the urban design plan with small land dedicated to vegetation (dense) and water bodies for a comfortable and pleasant thermal condition. To conclude, the findings of this communication aid in comprehending the significance of a mixed landscape, i.e., a significant proportion of vegetated/open spaces and water bodies inside the urban jungle. This study complements earlier research related to the rise in LST due to changing land use (Deng, Wang et al., 2018; Estoque, Murayama et al., 2017; Feizizadeh and Blaschke, 2013; Pal and Ziaul, 2017) and contributes to the understanding of how microclimatic conditions are affected by modifications in the landscape. The study focused on the KMA region and found evidence of the LST changes the metropolitan is experiencing as a consequence of a considerable increase in urban areas.

The research was, however, limited in a few ways, out of which one of the most important was not consideringatmospheric water vapour, which severely impacts the LST.In addition, the accuracy of estimating LST could not be assessed in this study as the ground level data was notcapturedowing to the unforeseen situation of Covid19.In the future, research should be conducted to help comprehend the diurnal as well as the seasonal fluctuations in LST caused by landscape alterations while taking other factors into account. A micro level investigation is also required to determine specific factors and agents responsiblefor the changed LST.The findings of this study, together with input from scientists, climate experts, and environmentalists, can aid in the development of new and improved policies and guidelines to provide a healthy and comfortable urban environment for inhabitants.

## AUTHOR CONTRIBUTIONS

B.H.A contributed to formulating strategy, data collection, technical inputs, Funding for the work and paper writing about 40% of the total work. N.G. contribution to development of methodology, data collection, analysis of data and method of critical thinking along with inputs in paper writing about 60% of contribution. All authors have read and agreed to the published version of the manuscript.

## ETHICS DECLARATION

The authors declare that they have no conflicts of interest regarding the publication of the paper.

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