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Review Article

Urban Heat Island Effects; A De-Greening Process, Implication for Environmental Sustainability and Quality of Urban Life. A Review

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Abstract

Urban Heat Island is formed as a result of the degreening of natural vegetative surfaces, due to the development and expansion of an area into artificial impervious surfaces leading to an increase in the ambient and surface urban temperature of the city more than the adjoining rural areas. Urban surfaces are replaced by impervious surfaces such as roads, buildings, and paved surfaces while the rural surfaces are defined by the porous vegetative cover. Temperature differentials between urban and rural adjoining areas are high in urban areas due to high reflectivity and emissivity (high albedo) of urban surfaces. The impacts on humans and the environment are manifold e.g., heat stress, heat cramp, dehydration, low productivity and comfort of ambient city dwellers, reduction in vegetative cover, high evaporation, and evapotranspiration in plants and reduction in soil and water quality of urban areas.

This study critically reviewed the impacts of urban heat island on humans and the environment to reveal novel areas for future research and global replicability. Studies reviewed revealed the applicability of in-situ weather monitors (handheld digital thermometer), conventional weather stations, satellite imageries (MODIS LST and Landsat), and modeling (Weather Research/Forecasting and Urban Canopy Models) in the investigation of urban heat island impacts on human comfort and environmental sustainability.

Mitigation measures are urban forestation, parks cooling islands and gardens, tree incorporation in residential areas, and redesigning of buildings with white surfaces to reduce the temperature of urban areas. Urban heat island studies need to be redefined to accommodate changes and expansion in urban areas and emerging heat island effects in rural areas due to the rapidity in the physical and structural development of rural areas. There is a need for emphases on rural and urban canopy heat islands and the role of parking cooling islands in urban comfort and sustainability.

Keywords: Urban heat island; Park cooling island; Urbanization; Albedo; Temperature; Human comfort

Introduction

Urban Heat Island was first coined by Howard L [1], to describe a situation where the climate of a city and its adjoining areas are controlled by differential surface energy interaction [2]. Urban surfaces are characterized by man-made surfaces that possess varying heat capacity and thermal admittance to store heat. e.g., concrete, stones, bricks, and asphalt [3]. Urbanized surfaces modify the water and energy balance processes and alter the ambient air quality of a city [4,5] A warmer ambiance over built-up areas than the surrounding vegetated surface as a result of population growth and replacement of natural surfaces with artificial surfaces e.g., paved surfaces, roads, buildings, etc. is called a Heat Island [6,7]. This ambient heat (both sensible and latent) is associated with energy consumption from buildings, transportation, and industries which forms the integral functions of an urban area [8]. Urbanization is characterized by geometric changes in land surface structures due to construction of street canyons and buildings which alters the ambient and surface temperatures of cities than their adjoining rural areas creating a phenomenon called an Urban Heat Island (UHI) [4,9-11].

Urban Heat Island (UHI) influences the microclimate by changing the wind patterns, precipitation, temperature, and humidity of an area. The strength of UHI is determined by varying meteorological variables e.g., the clarity of the sky and calmness of the wind leads to very strong UHI effects as compared to turbulent mixing and wind speed which reduces the temperature of the planetary air [3]. Rural degreening and increasing carbon(iv)oxide levels in the atmosphere are precursors to an increase in diurnal surface urban heat island intensity [12,13]. This is consistent to the theory of Urban Boundary Layer which states that Heat Island intensity is proportional to the square root of the distance from Urban Boundary(coast) Takebayashi H and Senoo M [14] and decreases with the warmer condition over broad spatial and temporal scales [15]. UHI predominates nocturnally (due to the released of stored heat into the environment as longwave radiation) than diurnally and varies in seasons [3] e.g., UHI is weaker in summer than in winter in temperate regions, in wet than dry seasons in tropical regions and influenced by low wind effects [16]. UHI is linked with an apparent anticyclone movement anomaly that continuously increases the temperature of the earth's surface and is influenced by precipitation stressed soil conditions in transitional climatic zones [17]. Diurnal cycles of absorptions, cyclical radiation of solar energy and heat emissivity, and reflectivity from built-up areas are drivers of Urban Heat Island intensity in cities [18,19].

UHI is categorized into Surface and Atmospheric Heat Island, of which Atmospheric Heat Island is bifurcated into Urban Canopy and the Boundary Layer. Urban canopy describes the patterns of warming at a varying distance above the ground to the tallest building in the city, while the boundary layer heat island describes patterns of atmospheric warming from the lowest layer of the troposphere to the earth's surface. Surface heat island on the other hand describes patterns of heat warming from the ground. Urban canopy heat island is monitored through in situ micro weather instruments e.g., thermometers while boundary layer heat island is monitored through ground base conventional thermometers from weather stations and satellites remote sensed data (which captures spatial and thermal radiance) [20]. UHI has manifold impacts (Figure 1&2) on both Flora and Fauna, Climate, Energy and Water Consumption, Economy and Environment, Human Health and Thermal Comfort, Air Quality, Global Warming and Urban Quality Life [10,11, 21-29]. UHI are precursors to heat stress injuries among residents in the city, high water demand for large scale irrigation, high cooling energy consumption, green space degradation and formation of city smog [16,18] such as ground-level ozone formed as a result of a photochemical reaction between Volatile Organic Compounds (VOC) and Oxides of Nitrogen (NOX) [30,31] (Figure 1&2).

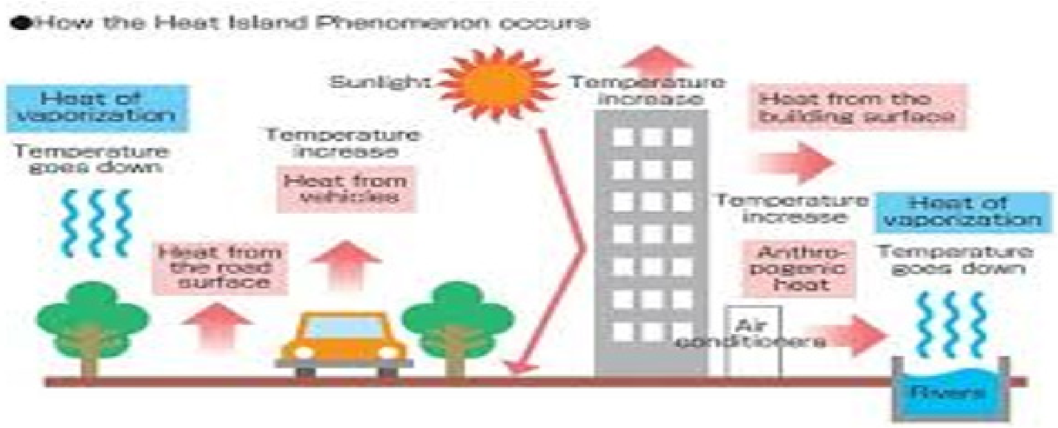

Figure 1: Diagrammatic Representation of Urban Heat Island Phenomenon.

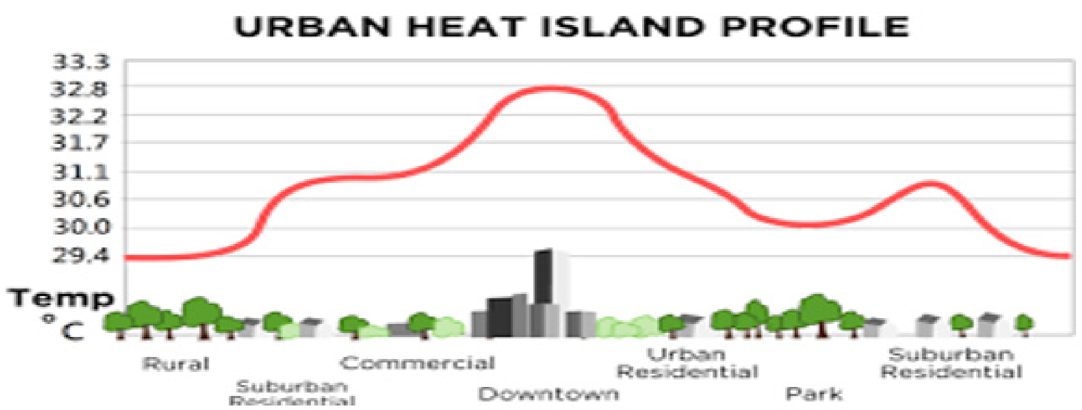

Figure 2: Urban Heat Island Profile.

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Cities account for 55% of the current world population and projected to 68% by 2050 to increase by two billion people due to population growth and urbanization, 90% of which will come from Africa and Asia [32]. Urbanization is projected to occupy over 1.8 to 2.4% of global cropland by 2030 decreasing crop and grain production globally [33]. Urban areas in 59 cities across Africa increased from 262.8 km2 in 2001 to 309.8 km2 in 2016 with the fastest cities amongst the Gulf of Guinea countries (Lagos, Nigeria) [12,13]. Economic losses resulting from global urban heating are projected to cost over 10 trillion dollars by 2100 [34]. Urban growth and expansion will be dominant in India, China, and Nigeria accounting for 35% of the world projected urban population between 2018 and 2050 at 416 million Indians, 255 million Chinese, and 189 million Nigerian urban dwellers respectively [32]. World Urban population has increased geometrically from 751 million in 1950 to 4.2 billion in 2018 with Asia accounting for 54% and Europe and Africa accounting for 13% each [32]. Also, the rural population in 2018 was 3.4 billion with Africa and Asia constituting over 90% of the world's rural population and India and China accounting for over 893 and 578 million rural inhabitants [32]. Megacities around the globe are projected to increase to forty-three with over ten million residents mostly in emerging and developing countries in Africa and Asia by 2030 with the fastest urban agglomeration hosting over a million people in both regions [32]. However, 61% of cities in eastern Europe and central Asia declined in scale and 11% in population between 2000 and 2010 [35].

In Nigeria, natural population growth has led to the reclassification of one's rural areas to peri-urban and urban centers ones a population of 20,000 benchmarks for an urban area is achieved [36]. Urban system structures in Nigeria are a pyramid with a megacity in Lagos, 7 metropolitan cities with over a million inhabitants, fifteen large cities with a population between 500,000 to 1 million, 19 medium cities with a population ranging between 300,000 to 500,000 and hundreds of peri-urban centers all experiencing population growth and expansion in magnitude [36]. Three urban centers are in transition to assume a metropolitan status by 2020 and they are Nnewi, Aba, and Uyo, while other metropolitan cities are Kano, Ibadan, Port Harcourt, and Abuja, etc. The World Bank projection of Nigerian Cities by 2030 stated that Nigeria will have 23 metropolitan cities with over a million-population accounting for 50% of 41 such cities in Sub-Saharan Africa. Migration to urban centers accounts for 60% of flows than in rural areas where emigration accounts for 40% [36]. Nigerian urban space is defined by four clusters between the north and southern regions of the country, and they are; Kaduna/Kano/Katsina clusters, Abuja, Nasarawa/Jos clusters, Enugu, Owerri, Aba/Port Harcourt, and Calabar clusters and the Lagos/Abeokuta, Ibadan/Akure and Oshogbo clusters. These are emerging megaregions connected by infrastructures that drive development [36].

This study is aimed at critically reviewing the effects of urban heats island effects on man and the sustainability of the environment across the tropical and temperate zones. Previous studies focused on regional reviews [3,12,13,37-45] which only revealed peculiar climatic heat island effects neglecting the comprehensive, robust, and enunciating variation of the impacts of urban heat island globally. This review proffered workable mitigative measures and was not limited to grey and novel areas for future research and replicability.

Review of the Literature

Diurnal and nocturnal heat island intensities

Urban heat Island is diurnal, nocturnal, and seasonal in intensity. A study to monitor variation in diurnal and nocturnal urban heat intensity by Umamaheshwaran R and Qihao W [46], in Indianapolis revealed a magnitude of 1-5°C during the day and 1-3°C at night and intense north of Marion and Hamilton County due to development and modification of Marion county's landscape. During the summer in Valencia, Spain, 43], recorded an average positive temperature of 1.4°C in the late night and early mornings, temperature, and precipitation of 8.5°C, 7.7°C, and 26.5mm and 123mm respectively between 1966 to 2014 in both airport and city stations. The land surface temperature during the 25 to 27 day of August was the hottest at 42.2°C while LST and AT differentials were high during the day at 10°C than at night at 2.5°C due to variation in the physical nature of both LST and AT and alteration in surface-atmosphere interaction between the planetary and urban canopy layers. Rural greening has been proven to be a precursor to urban heat island intensity, a study by [12,13] revealed a yearly increase in average diurnal and nocturnal surface urban heat island intensity (SUHII) of 42.1% and 30.5% in 397 cities globally due to rural greening which contributes 0.09°C (22.5%) per decade to increase diurnal SUHII than nocturnal SUHII. The diurnal trend in SUHII varied seasonally in 397 cities and highest in summer while diurnal SUHII correlated to an Enhanced Vegetative Index (EVI) of 58.9% in 397 cities due to higher EVI variation between rural and urban areas.

The structure of the urban space in terms of the inter and intra urban green spaces between rural areas influences the atmospheric chemistry and energy consumption of a city. Yadav N, et al. [3] in the NPL and SAFD regions of Delhi, India revealed a similarity in intra and intercity heat islands as the SAFD built-up areas showed higher UHI effects than vegetated NPL areas within the city, UHI was stronger during the day at 3°C than nocturnally at 0.2°C between the SAFD and the NPL regions and capable of increasing the energy demand and carbon(iv) oxide emission levels of the city by 1856GWh from 37.87GWh and 0.031 to 1.52 million ton of CO_2 levels and contributing to greenhouse gases and human discomfort in the city.

Variation in physical, climatic, and demographic characteristics of cities also creates distinction in the intensity of urban heat island. Chinas hot wet southeastern, cold dry northwestern climates and large water bodies influence the SUHII and Land Surface Temperature disparities between the urban, peri-urban, and rural areas of China [47]. In Ethiopia, the Population growth of 739,581 recorded between 1960 and 2000 corroborated with a mean maximum temperature rise of 1.7°C [7]. Also, in the City of Akure, Nigeria, Land Surface Temperature (LST) increase of 28.52°C in 1986 to 38.42°C in 2006 was consistent with a population growth of 120,531 in 1980 to 486,569 in 2006 due to the transformation of the city into roads, pavements, and built-up areas [48]. LST was consistent with urban growth between 1986 to 2016 in the city of Kano, Nigeria. LST increased from 360C to 410C consistent with built-up areas from 49.18km2 to 87.13km2 between 1986 and 2016 [45]. Diurnal and nighttime hourly temperature of 26.20C and 35.30C due to the low cooling capacity of the urban surfaces led to a demand for electricity and air conditionals in the dry season in Calabar, Nigeria, [49]. According to Youn Young C, et al. [37] the normalized difference vegetation index (NDVI) over Seoul, Tokyo, and Beijing mega cities revealed higher fractional coverage in the rural than urban centers due to higher cooling effects via evapotranspiration and shadowing effects from vegetation during the day resulting in higher proportional intensities in SUHI and vegetation differentials between the rural and urban areas. NDVI is inversely related to non-transformed surfaces, a study by Adebowale BI and Kayode SE [48], in the city of Akure in Nigeria revealed a high NDVI cum non-transformed surface in 1986 due to low population as compared to a low NDVI cum transformed urban surfaces in 2006. Urban heat island also alters both diurnal and nocturnal land/sea breeze circulation and pollution diffusion of a city [50].

Urban heat island monitoring

Urban Heat Island Investigation is determined by either atmospheric or surface heat island effects. Atmospheric heat island is bifurcated into the Urban canopy and Boundary layer. While the Urban canopy heat island utilizes in situ weather monitors, the boundary layer heat island uses conventional ground-based weather stations and surface heat island utilizes satellite data to monitor varying temperature levels between the urban and rural areas. e.g., dry bulb thermometers were used to record the hourly temperature of (16) sixteen sites (Etim-Edem Park, Eleven-Eleven Bus Stop, Murtala Mohammed Highway, Watt Market, Ndidem Usang Iso, Calabar Road, Etta Agbor, Parliamentary Road, Atimbo Road, Mount Zion, Airport Road, IBB Road, White House, Mary Slessor and Ekpo Abasi), etc. to investigate temperature differentials in the city of Calabar [49]. Also, in Akure City, Nigeria, simultaneous measurements of temperature and humidity were taken from shielded portable Lascar EL-USB-2 temperature/humidity data loggers, at 5-minute intervals mounted on a lamppost above head height of 3m in the city and on a mast at the airport for a year to evaluate bioclimatic variables [51]. In Douala, Cameroun's handheld digital thermometer was used to investigate the intensity of urban canopy heat island [16].

Over wider areas, the deployment of satellite imageries has aided the investigation of surface temperature differentials over temporal scales e.g., MODIS LST and Landsat TM, ETM and OLI/TIRS, etc. Moderate Resolution Imaging Spectroradiometer (MODIS) Land Surface Temperature (LST) derived from Terra and Aqua Satellites can be used to investigate surface urban heat island intensity based on varying spatial resolutions [47,52]. MODIS 1km spatial resolution LST and Enhanced Vegetative Index (EVI) data for 17 years have shown the influence of rural greening on surface urban heat island intensity [12,13]. A study by Youn Young C, et al. [37] utilized the MODIS data set to calculate the Normalized Difference Vegetative Index (NDVI) for Surface Urban Heat Island and Vegetative Cover over the cities of Seoul, Tokyo, and Beijing. MODIS LST non-parametric three-dimensional model diurnal and nocturnal thermal imageries can explore the impacts of UHII as discovered in Indianapolis [46]. In China, Yao R, et al. [47] investigated the seasonal influence of different data and methods on estimating the surface urban heat island intensity in thirty-one cities using both the MODIS Terra and Aqua Satellites Data. Studies have established the nexus between land use land cover changes and land surface temperature in the investigation of urban heat island intensity using Landsat thematic mapper satellite data and Operational Land Imager (OLI)/ Landsat images [41,53-55] investigated the effects of landscape composition and pattern on land surface temperature in megacities of Manila, Jakarta, and Bangkok in Southeast Asia using Landsat-8 OLI/TIRS data, urban-rural gradient, multiresolution grids, and spatial metrics-based techniques. Similarly, in Nigeria, Landsat TM, ETM+, and OLI/TIRS data have been used to monitor the influence of land use land cover changes on SUHII in Enugu, Onitsha, Kano, and Kaduna Cities [20,44,45,56-58]. Sheng l, et al. [59], evaluated the distinction in urban heat island intensity in Hangzhou China comparing Landsat LST data and air temperature data from conventional weather stations. Due to the Instantaneous field of view (IFOV) errors that exist in Landsat data, Land surface temperature studies in Berlin Germany has been strongly correlated with Impervious Surface Area which utilizes Neighborhood Pixels derived from the Kernel Density Estimation Method to reveal an enunciated SUHII than evaluating temperature differentials between urban and adjoining rural areas [60].

The integration of satellite infra-red imageries with thermal heat index has unraveled the thermal comfortability of inhabitant in a city e.g., Bozhou city in China Li Y, et al. [11]and Valencia in Spain [43]. The thermal perception of inhabitants in a city derived by analyzing the performance of cool pavement, urban vegetation, and cool roof using the Mediterranean Outdoor Comfort Index (MOCI) has been investigated in Rome [61]. In Akure City, Nigeria, Balogun, and Ahmed (2014) integrated the relative strain (RSI), discomfort (DI), and thermo-hygrometric (THI) indexes to investigate varying bioclimatological variables between inhabitants of urban and adjoining rural areas in the city. Modeling is an alternative method in the quantification of urban heat island intensity, Li H, et al [40], in Berlin Germany and Feng C, et al. [42], in Hangzhou, China, and Takebayashi & Senoo, (2017) in Tokyo, Osaka, and Nagoya cities of Japan quantified UHII and its physical mechanism using Weather Research/Forecasting and Urban Canopy Models. The BEP+BEM scheme was used to investigate the nexus between surface air temperature and wind speed on UHII over Madrid in summer [8]. A study by Weng Q, et al. [38], in Iran integrated the Shannons entropy, Pearson chi-square, surface urban heat island ratio, and degree of goodness indexes to monitor the spatial/temporal variation of SUHII in Babol City.

Mitigation Measures

Urban forestation increases park cooling island effects and reduces both air and surface temperature of the city through shading and evapotranspiration from broad canopied tall trees and vegetated surfaces. [62-64]. An increase in the city tree canopy, urban wall greening, and urban parks and gardens prevents short wave radiation from hitting the earth's surface, reduces human exposure to direct solar radiation and improves human thermal comfort and enjoyment [39,65]. Plants leave uptake acoustic energy which helps in reducing noise pollution [66,67]and air pollution by absorbing O3, PM10, NO2, SO2 and CO pollutants in the city [68,69].

Greening of the earth's surface reduces greenhouse gases by absorbing increasing CO2 levels in the atmosphere [12,13]. Vegetation cover modifies the microclimate of a city by retaining precipitation and reducing soil and water loss [70,71]. A study by Akio O, et al. [72], evaluated the suitability of simulating trees, grasses, and shrubs as mitigative measures to the impacts of urban heat island in Nagoya Japan. Mitigative measures were simulated for two different scenarios using 100% grass in the first scenarios, 70% grass, and 30% trees in the second. The results revealed a 7.26oC reduction in land surface temperature in summer on both scenarios.

According to Series PP [73], the retrofitting of public transport with ventilation and white roofs reduces solar heat gain; retrofitting buildings by adding light-colored roofs provide a cooling effect and increasing surface reflectivity using light-colored or white paint on the surface of construction materials reduces the radiation absorption of urban surfaces. Furthermore, early warning systems and educational campaigns to educate the general public on precautionary measures during heat peaks are critical.

Research Gaps

The studies reviewed, [10,11,20,37,42,43,45,49,50] focused on urban centers where heat island phenomenon is ignoring rural areas Feng C, et al. [42] where development and population have increased in recent times [32,35,36]. There is a need for the reclassification of our urban and rural landscape based on standard urban population bench march for urban heat island studies in these emerging urban and peri-urban areas.

Urban heat island effects are of three types, the surface, urban canopy, and boundary layer heat island effects, majority of the studies focused on the surface and boundary layer heat island effects [10,11,20,37,43,45,46,49,56-58,72] with little attention on urban canopy heat island effects Feng C, et al. [42], which is fundamental to microclimatic studies on vegetation diversity and growths and survival of plants and animal species.

Studies on surface heat island effects [37,48] focused more on the analysis of variation in plants species using the normalized difference vegetation index (NDVI), land use and land cover classifications, etc. ignoring the changes on animal species as a result of urban heat exposure. There is a need for surface heat island studies to evaluate the changes in animals and plant diversity as a result of urban heat island effects at the micro-level.

Studies on the impacts of park cooling island on urban heat reduction and thermal comfort are scanty.

Conclusion

Urban heat island is a ubiquitous phenomenon that involves the degreening of the natural vegetative surface into impervious surfaces as a result of urbanization. Rural areas globally especially in Asia and Africa are emerging into peri-urban and urban centers due to the destruction of the natural landscape for the development of urban infrastructures like roads and buildings. These developments have changed the microclimate of the area and have an increase in radiation levels in rural areas. Vegetative protectors with a high albedo and low emissivity are declining due to urban development and giving way to urban structures with low albedo and high emissivity. This has increase urban discomfort especially to ambient workers in cities. Studies on urban heat island are imperative for the sustainability of urban areas and the comfort of city dwellers. This will assist policymakers to pursue the integration of urban development and greening of the urban spaces with the use of eco-friendly sources of energy for the improvement of the health and well-being of our urban dwellers [74-80].

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Conflict of Interest

No conflict of interest.

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