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A REVIEW OF URBAN HEAT ISLANDS: CAUSES, EFFECTS, AND MITIGATION

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ABSTRACT

The high influx of rural dwellers to urban areas has resulted in the rapid replacement of vegetation by buildings and roads in urban areas. This densely populated urban area experiences significantly higher temperatures than the surrounding rural areas, a phenomenon called the urban heat island (UHI). This paper attempts to review the causes and effects of UHI, and mitigation measures that could be adopted to improve the urban microclimate. Poor urban planning, anthropogenic heat, air pollution, urban geometry, and reduced vegetation, among others, contribute to UHI formation, mainly in densely developed cities. This phenomenon is responsible for the decline of climate, human thermal discomfort and mortality, energy consumption, and water quality deterioration. Mitigation strategies discussed in this paper include green roofs, cool roofs, green vegetation, cool pavements, and urban planning. Urban dwellers should be encouraged to increase shading around their homes, install green and cool roofs, and use energy-efficient appliances and equipment. Proper landscape design in urban planning, using cool pavements, such as highly reflective and permeable pavements, should be encouraged by urban planners as this would be a potential strategy to ameliorate the urban microclimate. Also, government and non-governmental organizations should create awareness of the effects of urban heat islands and strategies to mitigate them

Keywords: *urban heat island, causes, effects, and mitigation measures*

INTRODUCTION

In our current world and especially in developing countries, urban populations are increasing rapidly in size as more and more rural dwellers are migrating to cities in the hope of gaining a better standard of living. This urbanization is driven by pull factors that attract people to urban areas and push factors that drive people away from the countryside. As a result of this rapid urbanization, large amount of energy is required by cities to function properly. Although cities occupy only about 2% of the earth's surface, city dwellers consume over 75% of the total energy resources available to carry out everyday activities in the urban environment (Madlener & Sunak, 2011). Land transformation due to urbanization has also caused noticeable climate changes, including increased energy demands and air pollution thereby impacting the quality of urban life (Gray, et al., 2000; Alfraihat et al., 2016). With more than half of the world's people living in urban areas (55%, up from 30%), urbanization determines the spatial distribution of the world's population and is one of the four demographic mega-trends, with the growth of the global population, population ageing, and international migration (World Urbanization Prospects, 2019).

There is a predictable change in the urban environment as a consequence of this growth. Buildings and roads begin to replace open space and vegetation, causing surfaces that were once pervious and moist to become impervious and dry. These changes lead to the development of a phenomenon known as an urban heat island (UHI). Urban Heat Islands (UHI) is a situation where the cities or metropolitan areas' ambient temperature is dramatically altered and become warmer than the surrounding rural areas (Oleson, et al., 2005; Gago, et al., 2013; Alfraihat et al., 2016). The makeup of urban areas differs across the world, causing the heat island effect to be more magnified in certain locations rather than others due to geographic variances. Researchers suggest the annual mean air temperature of a city with one million or more people can be 1.8 to 5.4°F (1 to 3°C) warmer than its surroundings, and on a clear, calm night, this temperature difference can be as much as 22°F (12°C). (U.S. EPA, 2008).

In Nigeria, just like many other African countries, the capital cities are often faced with the problem of rapid urbanization, which contributes majorly to the UHI intensity (Isioye, et al 2020). According to Aljazeera (2019), the months of March, April and May 2019 experienced extreme heat, with the Nigerian Meteorological Agency (NiMET) saying that the temperature rise has been affecting most parts of the country, including coastal areas, with temperatures well above 35^{o}C.

The Urban Heat Island (UHI) is a phenomenon that affects millions of people worldwide. The UHI affects urban quality of life through its impacts on human health, ecosystem function, local weather and climate. There is a direct relationship between peak UHI intensity and heat related illness and fatalities (Oleson, et al., 2005; U.S. EPA, 2014; Alfraihat et al., 2016). UHIs occur when a densely populated urban area experiences significantly higher temperatures than the surrounding rural or less populated area. When naturally vegetated surfaces such as grass and trees are replaced with non-reflective, impervious surfaces, those surfaces absorb a high percentage of incoming solar radiation, causing a warming effect (Taha, 1997). The heat 'island' is the result of an unintended climate alteration due to a modification of land surfaces, caused mainly by an increase in urbanization and anthropogenic activities. Urban heat islands are an important issue because they can pose both health and environmental risks due to increased heat exposure and enhanced levels of air pollutants, specifically ozone. According to Amiri et al. (2009) , in several literatures across the globe, built-up areas and bare land have been shown to accelerate the effect of UHI, whereas green space and water reduce the UHI intensity. The warming effect that results from urban heat islands is an example of local climate change. Local climate changes differ from global climate changes in that their effects are confined to the local scale and decrease with distance from their source. Global climate changes, such as those caused by excess greenhouse gas emissions, are not locally or regionally confined, though the impacts from urban heat islands and global climate change are often similar.

For example, both urban heat islands and global climate change can increase energy demand, mainly through heating and cooling, and both can cause an increase in air pollution and greenhouse gas emissions.

2.0 Causes of Urban Heat Islands

Urban heat island formation is as a result of several factors:

2.1. Reduced Vegetation in Urban Areas: Heat islands are caused by a reduction of vegetation and evapotranspiration, a higher presence of dark surface with low albedo, and increased anthropogenic heat production (Mohajerani, Bakaric, & Jeffrey-Bailey, 2017). In rural areas, vegetation and open land typically dominate the landscape. Trees and vegetation provide shade, which helps lower surface temperatures. They also help reduce air temperatures through a process called evapotranspiration, in which plants release water to the surrounding air, dissipating ambient heat. In contrast, urban areas are characterized by dry, impervious surfaces, such as conventional roofs, sidewalks, roads, and parking lots. As cities develop, more vegetation is lost, and more surfaces are paved or covered with buildings. The change in ground cover results in less shade and moisture to keep urban areas cool. Built up areas evaporate less water, which contributes to elevated surface and air temperatures. Lesser trees means less cooling efficiency. Trees intercept the solar heat and also absorb for their own photosynthesis, (Akbari et al. 2001).

2.2 Properties of Urban Materials: Properties of urban materials, in particular solar reflectance, thermal emissivity, and heat capacity, also influence urban heat island development, as they determine how the sun's energy is reflected, emitted, and absorbed. Urban areas typically have surface materials, such as roofing and paving, which have a lower albedo than those in rural settings. As a result, built up communities generally reflect less and absorb more of the sun's energy. This absorbed heat increases surface temperatures and contributes to the formation of surface and atmospheric urban heat islands. Although solar reflectance is the main determinant of a material's surface temperature, thermal emittance, or emissivity, also plays a role. Thermal emittance is a measure of a surface's ability to shed heat, or emit long-wave (infrared) radiation. All things equal, surfaces with high emittance values will stay cooler, because they will release heat more readily. Most construction materials, except for metal, have high thermal emittance values. Thus, this property is mainly of interest to those installing cool roofs, which can be metallic. See the "Cool Roofs" chapter of the compendium for more information.

Another important property that influences heat island development is a material's heat capacity, which refers to its ability to store heat. Many building materials, such as steel and stone, have higher heat capacities than rural materials, such as dry soil and sand. As a result, cities are typically more effective at storing the sun's energy as heat within their infrastructure. Downtown metropolitan areas can absorb and store twice the amount of heat compared to their rural surroundings during the daytime (Christen, et al. 2004).

2.3 **Urban Geometry.** The dimensions and spacing of buildings within a city influence wind flow and urban materials' ability to absorb and release solar energy. In heavily developed areas, surfaces and structures obstructed by neighboring buildings become large thermal masses that cannot release their heat readily. Cities with many narrow streets and tall buildings become urban canyons, which can block natural wind flow that would bring cooling effects. During the day, urban canyons can have competing effects. On the one hand, tall buildings can create shade, reducing surface and air temperatures. On the other, when sunlight reaches surfaces in the canyon, the sun's energy is reflected and absorbed by building walls, which further lowers the city's overall albedo—the net reflectance from surface albedo plus urban geometry— and can increase temperatures (Sailor, et al 2002). After sunset, the process of cooling in cities is much slower than the countryside. This is due to the existence of high thermal capacity of materials (e.g., concrete, asphalt) in urban areas, i.e., cities absorb high amount of heat during the day and release it slowly over night. As a result, UHI is much intense at night. Geographical characteristics of a city may also worsen night time UHI intensity(Deilami, et al. 2018). In the case of Tehran, for example, a large number of high rise-buildings prevent breeze to pass through the city from the surrounding mountains (Haashemi et al., 2016).

2.4 **Anthropogenic Heat:** Anthropogenic heat contributes to atmospheric heat islands and refers to heat produced by human activities. It can come from a variety of sources and is estimated by totaling all the energy used for heating and cooling, running appliances, transportation, and industrial processes. Anthropogenic heat varies by urban activity and infrastructure, with more energy-intensive buildings and transportation producing more heat (Voogt,2002). Anthropogenic heat typically is not a concern in rural areas and during the summer. In the winter, though, and year round in dense, urban areas, anthropogenic heat can significantly contribute to heat island formation (U.S EPA,2008).

2.5.Weather and Geography. Calm and clear weather conditions result in more severe heat islands by maximizing the amount of solar energy reaching urban surfaces and minimizing the amount of heat that can be carried away. Conversely, strong winds and cloud cover suppress heat island formation. Geographic features can also impact the heat island effect. For example, nearby mountains can block wind from reaching a city, or create wind patterns that pass through a city(U.S EPA,2008)

3.0 Impacts of Urban Heat Islands

One of the most important factors influencing the quality of life in urban areas is the urban microclimate (Rehan,2016). The effects of urban island heat include degradation of the living environment, increased cooling energy usage and associated costs, intensification of air quality problems (e.g., the formation of large amounts of smog and air pollutants), impact on human health, comfort, and increased thermal stress and water quality deterioration(Mohajerani, et al.2017, and Li, et al. 2013).

3.1 Human Health and Comfort

Increased daytime surface temperatures, reduced nighttime cooling, and higher air pollution levels associated with urban heat islands can affect human health by contributing to general discomfort, respiratory difficulties, heat cramps and exhaustion, non-fatal heat stroke, and heat-related mortality. According to Murage et al.(2017), heat exposure during the night contributes to heat-related mortality, and the impact is most prominent when hot nights follow hot days. Urban heat islands can also exacerbate the impact of heat waves, which are periods of abnormally hot, and often humid, weather. Sensitive populations, such as children, older adults, and those with existing health conditions, are at particular risk from these events. High temperatures in urban areas increase residents' vulnerability to heat waves and climate warming (Ziter, et al. 2019).

3.2. Water Quality

Surface urban heat islands degrade water quality, mainly by thermal pollution. Pavement and rooftop surfaces that reach temperatures 50 to 90°F (27 to 50°C) higher than air temperatures transfer this excess heat to stormwater (U.S EPA,2008, Krause, et al. 2004). High temperatures of urban surfaces can increase stormwater runoff temperatures and cause thermal pollution of receiving water bodies(Zeiger, et al 2015). Water temperature affects all aspects of aquatic life, especially the metabolism and reproduction of many aquatic species. Rapid temperature changes in aquatic ecosystems resulting from warm stormwater runoff can be particularly stressful.

3.3.**Energy Consumption**

One of the most critical factors that increases energy use in urban areas is the formation of UHI (Shahmohamadi, et al. 2011). Higher air temperatures cause an increased demand in energy consumption through air conditioning. The increased demand for energy puts excess pressure on the power grid and can sometimes result in blackouts or brownouts during hot summer months (U.S. EPA, 2008). Elevated air temperatures can increase the maximum energy consumption for air conditioning by 5 to 10% (Akbari,2005). According to Akbari et al. (2001), each 1 ◦C rise in daily maximum temperature beyond a threshold of 15 ◦C to 20 ◦C may increase maximum energy consumption by 2% to 4%, respectively. Decreasing outdoor temperature by 1 ◦C during peak time, cooling energy consumption could be decreased by 6% (Roxon et al. 2020).

3.4. Air pollution and Greenhouse gas emission

Elevated air temperatures increase electricity generation by power plants, leading to a higher level of air pollution and greenhouse gas (GHG) emissions (US EPA, 2008). Such conditions increase the rate of ground-level ozone formation, one of the major components of photochemical smog that is harmful to the environment. Photochemical smog is produced in photochemical reaction when primary air pollutants (e.g., carbon monoxide (CO), carbon dioxide (CO2) sulfur dioxide (SO2), nitrogen oxides (NOx), suspended particulate matter, and volatile organic compounds (VOCs) react with secondary air pollutants such as NO2 and ozone (O3) (Gorsevski et al. 1998, Gray, et al 1999, Golden, et al. 2004).

4.0 Mitigation of Urban Heat Island

The UHI effects can be reduced by proper landscape design in urban planning (Unal et al. 2020). According to Martilli et al. (Martilli et al.2020) "the need for mitigation, the degree of mitigation needed, and the efficacy of a mitigation strategy must depend only on the thermal characteristics of the urban area, and not their difference from those of the surrounding rural areas". The major strategies to mitigate the UHI effect are described below:-

4.1 Green Vegetation

Increasing the amount of vegetation is one of the most effective strategies to mitigate the effects of the urban microclimate. Trees contribute to reducing the heat island effect by their evapotranspiration (Akbari et al.2001).

In urban areas, where only a fraction of the surface is covered by vegetation and surfaces tend to be water-resistant, potential surface cooling from vegetation and soil is reduced (Rosenzweig et al., 2006). Trees and vegetation help cool surface air temperatures through shading and evapotranspiration, making vegetation a simple and effective way to reduce urban heat islands. Evaporation, the conversion of water from a liquid to a gas, occurs in the surface of the soil around vegetation and from trees as they intercept rainfall on leaves. Transpiration takes place when trees and vegetation absorb water through their roots and emit it through their leaves. Together these processes work together to form the process of evapotranspiration which works by using heat from the air to evaporate water, cooling the air in the process (U.S. EPA, 2008).In addition to the benefits from evapotranspiration and shading, trees and other large vegetation can also serve as windbreaks to reduce the wind speed around buildings (U.S. EPA, 2008). These benefits can have both positive and negative effects in the summertime, however, in the wintertime, reducing wind speeds can provide substantial energy benefits.In order for trees to provide the most energy efficient benefits, they must be planted strategically around buildings and other infrastructure. Researchers have found that a building's height, orientation, and distance between trees and vegetation can affect the rate of cooling, therefore, trees can be harmful to an energy efficiency strategy if they block useful solar energy in the winter, when the sun is low in the sky, without providing much shade during the summer, when the sun is high in the sky (U.S. EPA, 2008).

4.2. **Urban Planning**

Proper urban planning can also play a vital role in the mitigation of the UHI effect. Yamamoto (2006) has described an urban planning approach situated on the bank of river. His suggestion is to build the buildings in such a way that wind path is created for cool airflow from the river into the city. If buildings are built parallel to the direction of river, no airflow will occur in to the city. If the buildings are positioned at a 450 angle, wind will get channel if it flows only in one direction. But if flows from the opposite direction, it cannot get away inside the city. However, airflow will occur in case the buildings are perpendicular to the river. He also mentioned that this option is expected to play a major role in the fore coming days and it deserves further attention. In other types of cities, it is expected that if there is sufficient amount of free space and channel to circulate the wind, it will help to minimize the effect of the urban microclimate.

4.3. Green Roofs

A green roof, sometimes referred to as a living roof, is a rooftop that has a vegetative layer growing on top. As with trees and vegetation elsewhere, green roof vegetation can provide shade and cool the ambient air through evapotranspiration. A green roof can help to reduce surface temperatures which helps buildings stay cooler because less heat flows through the roof and into the building (U.S. EPA, 2008). Razzaghmanesh et al. (2016) stated that green roofs could be an effective strategy to mitigate the UHI effects. They reported that covering 30% of the total roof area with green roofs could reduce surface temperature by 0.06 ◦C. A recently published study showed that planting trees in urban areas can significantly reduce air temperatures during hot days with a maximum temperature above 30 ◦C (Razzaghmanesh et al. 2021).

In addition, lower green roof temperatures result in less heat transfer to the air above the roof, which can help keep urban air temperatures lower as well (U.S. EPA, 2008). Green roofs help to improve human health and comfort by providing and cooling effect in buildings during the summertime and an insulating effect in buildings during the wintertime. In addition, green roof vegetation provides habitats for all kinds of urban animal and insect life

There are two types of green roof systems: an extensive green roof and an intensive green roof. An extensive green roof is typically made up of hardy, alpine-like groundcover (U.S. EPA, 2008). These roofs are designed to require little human maintenance or interference once they are established. Because extensive green roofs are made up of a thin layer of vegetation, they do not require much added structural support, making them a cost-effective option. On the other hand, an intensive green roof is more akin to a fully accessible garden or park (U.S. EPA, 2008). Intensive green roofs require more structural support to accommodate extra weight. In addition, they need irrigation systems to keep them growing.

4.4 Cool pavement

Cool pavements represent various materials and technologies used in pavement modification to lower their surface temperature and the quantity of heat released from their surface compared to traditional pavements (US, EPA 2008). Using cool materials with high reflectivity and high emissivity can ameliorate thermal conditions in urban areas (Li et al. 2014 , Kyriakodis et al 2018), improve air quality, and reduce electricity demand for air conditioning (Sen et al. 2019, Akbari et al .2012).

Traditional pavements such as concrete and asphalt can reach temperatures of up to 120–150°F (48–67°C) in the summertime (U.S. EPA, 2008). These surfaces contribute to urban heat islands, especially at nighttime, by trapping and storing heat during the day re-releasing it at night. Hot pavements can also heat stormwater as it washes over the pavement and into local waterways, causing the water to warm and impairing water quality. Cool pavements are designed to reflect solar radiation to help lower surface temperatures and reduce the amount of heat absorbed into the pavement. Solar reflectance, or albedo, and thermal emittance work together to keep cool pavements cool. Permeability is an additional factor that must be included when manufacturing cool pavement. Permeable pavements allow air, water, and water vapor to pass into the pavement through voids and into the soil or other supporting materials below. Wet pavements can lower surface temperatures through evaporative cooling.

However, use of high albedo materials for roads and highway pavement may not be so much effective because of the skyview factor. Even if, it is used, some of the reflection will be intercepted by the buildings surrounding it. In addition to it, a large proportion of it is covered by vehicles in most of the daytime. The problem of glaring which is associated with cooling roofs is also accompanied with the high albedo pavements. Sailor (2006) states that high albedo pavements may increase visibility at night, thus reduces the requirement of light. He continues that at day time glaring will have negative effect regarding visibility. Again, the wearing action will lessen the reflectivity of pavements within a very short time due to vehicle movement. So, Durability and visibility should also be taken into account before going to take the initiative.

Cool pavement has the potential to significantly reduce ambient air temperatures. This would result in significant benefits in terms of lower energy use and reduced ozone levels(Wang et al 2018, US EPA 2018). Decreased energy demand will result in lower associated air pollution and greenhouse gas emissions, and Cool pavements with lower surface temperatures will help to reduce the temperature of stormwater runoff before it enters nearby water bodies.

4.5. Cool Roof

A cool roof with high albedo reduces the net radiation by reflecting more incoming solar radiation and thus reducing the sensible heat flux and absorbed heat on the surface. The term cool roof refers to a roof that has been designed to reflect more sunlight and heat than it absorbs (U.S. Department of Energy, 2012). Cool roofs can be made of multiple materials such as a highly reflective type of paint, a sheet covering, or highly reflective tiles or shingles (U.S. Department of Energy, 2012). Cool roofing products can remain approximately 50 to 60°F (28-33°C) cooler than traditional materials during peak summer weather (U.S. EPA, 2008).

While both green roof and cool roof strategies reduce the level of heat available for transfer to the air or to buildings, the mechanisms for green roofs and cool roofs to reduce urban heat islands are different. A green roof increases the evapotranspiration in urban areas through plants and soil, while a cool roof increases the reflection of incoming solar radiation in urban areas by increasing the albedo of roof surfaces (Li, Bou-Zeid, & Oppenheimer, 2014)

Both roofs have high feasibility and have been widely recommended by professional agencies, such as the U.S. EPA.

A cool roof is designed to reflect more sunlight and absorb less heat than a traditional roof. The two radiative properties that characterize cool roofs are solar reflectance and thermal emittance. Solar reflectance, or albedo, measures a roof's ability to reflect sunlight and heat away from a building. Thermal emittance refers to the relative ability of the roofing material to release absorbed heat as invisible infrared light.

5.0 CONCLUSION AND RECOMMENDATION

UHI is gaining much attention around the world because the world is getting urbanized as it advances in technology. The existing conditions of a given urban area will determine the type of heat island mitigation strategies that will be most effective relative to the area. In most cases, widespread change of the urban fabric by changing the spacing of buildings and the layout of the city is usually not feasible. In terms of temperature reduction, cool roofs with the maximum roof albedo are more effective than green roofs with daily irrigation, especially at night (Xun et al. 2022). The recommendations are:

1 Proper landscape design in urban planning, using cool pavements, such as highly reflective and permeable pavements, should be encouraged by urban planners as this would be a potential strategy to ameliorate urban microclimate
2 Government and non-governmental organizations should create awareness on the effects of urban heat islands and strategies to mitigate it.
3 Urban dwellers should be encouraged to increase shading around their homes, install green and cool roofs, and use energy-efficient appliances and equipment.

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