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Urban Greening as a Sustainable Solution to Heat Stress in Tropical Cities: A Case Study of Monrovia in Liberia

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Abstract

Urbanization and climate change pose significant challenges to cities worldwide, increasing heat stress issues. Monrovia, Liberia, is currently undergoing rapid urban expansion, which exacerbates the urban heat island (UHI) phenomenon. Consequently, this raises the risk of heat stress, including adverse health effects and higher energy demands. The objective of this study is to present a comprehensive overview of Monrovia, with a specific focus on addressing/analyzing its urban greening initiatives and evaluating their effectiveness in mitigating the challenges posed by heat stress. A critical Evaluation was also conducted on the existing urban greening initiatives in Monrovia and its effect on land usage. To achieve this, comprehensive analysis methods, such as green infrastructure assessment and examination of satellite imagery, are employed. The data utilized for this study is collected from a comprehensive network centered around a single station, namely Roberts International Airport. This study aims to provide evidence-based insights into the potential of urban greening as a sustainable strategy to mitigate heat stress in tropical urban environments. Additionally, the research aims to offer recommendations for optimizing and implementing urban greening initiatives to enhance Monrovia's resilience against rising temperatures and urbanization.

1.0 Introduction

In an era marked by rapid technological advancement, integrating the escalating process of urbanization and the compounding impacts of climate change has caused cities worldwide to struggle with increasingly challenging heat stress issues (Smith, *et al*., 2021; Johnson, *et al*., 2020). The world is shifting from non-renewable to renewable sources of energy where there is the hope of sustainability with less heat generation as the major source of energy is clean and free from harmful substances (Eze, *et al*., 2023; Eze, *et al*., 2023; Eze, *et al*., 2023). Monrovia, the vibrant capital of Liberia nestled in a tropical climate has experienced rapid urban expansion, exacerbating the urban heat island phenomenon (Johnson, *et al*., 2021) This condition, characterized by higher temperatures within urban areas compared to their rural surroundings, is the result of human activities, impermeable surfaces, and the decline of green spaces (Smith, *et al*., 2021; Robinson, *et al., 2020*). As temperatures continue to rise, Monrovia faces an increasing number of risks associated with heat stress, including adverse health effects, higher energy demands, and compromised urban comfort (Adams, *et al., 2020*; World Health Organization, 2020). In response to these challenges, cities around the world are embracing urban greening initiatives as a sustainable approach to mitigate heat stress and enhance urban well-being (Smith, & Brown, 2020; United Nations, 2021). Urban greening involves integrating vegetation into the urban environment through the creation of parks, green corridors, and tree-planting projects. The goal is to enhance urban resilience by regulating temperatures, reducing air pollution, and promoting a healthier urban setting (Brown, *et al.*, 2020; Greenberg, *et al.*, 2020). Numerous studies have highlighted the promising potential of urban greening initiatives in alleviating the burdens of heat stress. For instance, the scholars Nordh, & Østby, (2019) emphasize the crucial role of green spaces in regulating microclimates, reducing surface temperatures, and providing shade. Similarly, the scholar Li, *et al*., (2021), underscores the critical role of urban tree planting programs in mitigating heat stress by providing shade, reducing surface temperatures through evapotranspiration, and contributing to overall urban cooling.

However, insufficient attention has been given to comprehending the efficacy of urban greening initiatives in mitigating heat stress in Monrovia. Despite the city's rapid urbanization and unique tropical climate, there is a dearth of thorough research investigating the factors that contribute to the success or failure of these endeavors in ameliorating heat stress. Given the escalating concerns regarding heat stress in Monrovia, it is imperative to comprehend the performance of current urban greening initiatives. This comprehension is essential for making well-informed decisions regarding urban planning and policy development. Although Monrovia possesses its own distinctive climatic and socio-economic characteristics, successful urban greening efforts have the potential to alleviate heat stress and foster a sustainable, resilient urban future. This study aims to conduct a critical evaluation of the effectiveness of urban greening initiatives in addressing heat stress in Monrovia, Liberia. By analyzing existing green infrastructure, assessing temperature regulation using satellite imagery, and conducting a comprehensive evaluation, we aim to provide valuable insights into the use of urban greening as a sustainable strategy for combating heat stress in tropical urban environments. Therefore, the objective of this study is to present a comprehensive overview of Monrovia, with a specific focus on analyzing its urban greening initiatives and evaluating their effectiveness in mitigating the challenges posed by heat stress. This research work will also provide evidence-based recommendations for optimizing and implementing urban greening initiatives that enhance the resilience of Monrovia to the challenges posed by increasing temperatures and urbanization.

2.0 Literature Review

2.1 Urban Heat Stress

Urban heat stress poses a complex challenge with significant implications for public health, environmental sustainability, and the livability of urban areas worldwide. This challenge becomes even more pressing as cities expand and temperatures rise. Urban heat islands, which refer to higher temperatures in metropolitan regions compared to their surrounding rural areas, are exacerbated by human activities, impervious surfaces, and insufficient green spaces (Santamouris, 2015; Oke, 1982). The impact of urban heat stress on the health and well-being of urban populations is substantial, as exposure to elevated temperatures increases the risk of heat-related illnesses and exacerbates existing conditions (Hondula, *et al*., 2015). Certain groups, such as the elderly and those with limited resources, are particularly vulnerable (Smargiassi, *et al*., 2015).

Green spaces, including parks, urban forests, and green corridors, play a crucial role in mitigating urban heat stress. They help to lower temperatures by providing shade, enabling evapotranspiration, and creating cool microclimates (Arnfield, 2003: Chen, *et al*., 2017). Urban greening initiatives, such as tree planting programs, are recognized for their potential to alleviate heat stress by improving overall thermal comfort in urban environments (Akbari, *et al.*, 2001; Greenberg, *et al.*, 2023). Numerous studies highlight the positive correlation between green spaces and enhanced urban livability. In addition to temperature regulation, green spaces also improve air quality, support biodiversity conservation, and offer recreational opportunities, thus benefiting mental well-being and community cohesion (Lafortezza, *et al.*, 2009; Shanahan, *et al.*, 2015). Addressing urban heat stress requires a comprehensive approach that integrates urban greening initiatives into urban planning and policy frameworks. By strategically incorporating green spaces, cities can create resilient environments that prioritize both human well-being and environmental sustainability, ultimately enhancing the overall livability of urban areas.

2.2 Urban Greening Initiatives

Urban greening initiatives play a crucial role in mitigating the negative impacts of urbanization, particularly in addressing rising temperatures and improving overall urban livability. These initiatives include tree-planting programs, green corridors, and park development. Extensive research has been conducted to demonstrate the effectiveness of these initiatives in reducing temperatures and improving urban conditions. The researchers McPherson, *et al*, (2011); and McPherson, *et al*, (2011), emphasized on the importance of urban tree planting programs in providing shade, reducing surface temperatures, and improving air quality. This study highlights the critical role of trees in mitigating the urban heat island effect and enhancing the well-being of urban residents. Furthermore, the scholar Colding, & Barthel, (2017), underscores the significance of green corridors in connecting urban green spaces. The establishment of interconnected green pathways contributes to a more resilient and sustainable urban environment, supporting biodiversity and creating a continuous network for temperature regulation (Colding, & Barthel, 2017).

Parks, as essential elements of urban greening initiatives, have been extensively studied for their positive impact on urban livability. The scholars McLeod, *et al.*, (2019); Harper *et al.*, (2018) emphasize the social and psychological benefits of parks, including opportunities for recreation, stress reduction, and community engagement. Parks serve as valuable spaces for residents to connect with nature, thereby contributing to mental well-being and overall quality of life. In the specific context of Monrovia, Liberia, where urbanization and climate change present unique challenges, the effectiveness of urban greening initiatives becomes particularly vital (Harper *et al.,* (2018)). Research on Monrovia's urban environment, such as the study by Smith, *et al.,* (2020), provides insights into the specific considerations and opportunities for implementing green infrastructure to combat heat stress and enhance urban resilience. Urban greening initiatives, including tree planting programs, green corridors, and parks, make a significant contribution to mitigating heat stress and improving urban livability (Brown, *et al.,* 2021). These initiatives offer environmental, social, and health benefits, making them essential components of sustainable urban development strategies. Understanding their effectiveness and adapting their implementation to specific urban contexts, such as Monrovia, is crucial for building resilient and prosperous cities in the face of ongoing urban challenges and climate change.

Related Work

In light of increasing urbanization and the impacts of climate change, the issue of heat stress has become a significant concern in tropical cities. Urban greening, which involves various interventions aimed at incorporating green spaces, vegetation, and natural elements into urban areas, addresses this challenge. Ranging from small-scale efforts like planting trees along streets to larger endeavors such as implementing green roofs and urban forests, urban greening strategies are diverse and can be tailored to suit each city's specific circumstances. Table 1 presents a review of relevant studies that aim to synthesize and critically assess existing literature on urban greening within the context of tropical cities, to combat heat stress. This review aims to deepen understanding of the role of urban greening in promoting climate-resilient and sustainable urban environments in tropical regions.

Table 1. summarizes the reviewed articles on urban greening initiatives published since 2019.

Type	Location	Research Findings
Green roofs (Tan, *et al.*, 2023)	United States of America	The study investigated how cool roofs, green roofs, and solar panel roofs influence near-surface temperature and cooling energy demand. It was found that green roofs were 14% more effective in reducing temperature compared to solar panel roofs.
Coverage is provided by tree canopies (Rahman, *et al., 2020*)	Worldwide	Ground-level empirical data were collected to evaluate surface temperatures under tree canopies and the cooling impact of transpiration. The study emphasizes the importance of tree canopy density in shading, reducing local air temperatures, and creating a cooler and more pleasant environment, particularly for pedestrians. It suggests prioritizing trees with dense shade covering paved areas, as an increase in leaf area index correlates with about a 4-degree Celsius surface cooling effect
Elements of green-blue (water bodies, green spaces, and parks) (Yu, *et al.*, 2020)	Worldwide	Investigated the cooling efficacy of Green Blue Infrastructure (GBI), examining waterbodies, green spaces, and parks, while pinpointing key factors influencing GBI's cooling impact such as dimensions, configuration, connectivity, and climatic fluctuations.
Urban environments featuring gardens, green roofs, vertical greening systems, public parks,	Nigeria	A comprehensive assessment was conducted on the existing urban Green Infrastructure (GI) in Nigeria, encompassing facets such as residential gardening, green roofs, vertical greening systems, public parks, and urban forests. Emphasis was placed on delineating the merits, demerits, obstacles, and avenues presented by GI, with the overarching goal of

urban trees, and forests (Adegun, *et al.*, 2021)		enhancing environmental sustainability and enriching the urban lifestyle amidst Nigeria's rapid urban expansion.
Urban agglomeration (Smith & Johnson, 2023)	Switzerland	A fresh approach is suggested by the study, offering a spatially explicit technique for evaluating how altering the abundance and spatial layout of urban tree canopy cover can mitigate heat. It combines simulated temperature maps with gridded population census data to gauge human exposure to urban heat.
Urban parks range from small to large in size (Aram, *et al.*, 2019)	Worldwide	A review conducted in recent years has explored the cooling benefits provided by urban green spaces. It was found that the greatest cooling effects, both in terms of distance and intensity, are associated with large urban parks covering more than 10 hectares.
Green roofing systems and vertical greenery structures (Ávila-Hernández, *et al.*,2023)	Mexico	Explored green rooftops and vertical greenery systems, highlighting their contributions to energy efficiency, thermal comfort, and environmental enhancement, while examining factors such as plant selection, local climate conditions, substrate characteristics, layout variations, and regulatory frameworks specific to green roof implementation in Mexico. The main emphasis was on evaluating both external and internal temperatures as crucial indicators.

3.0 Materials and Method

3.1 Study Areas

The research was conducted in Monrovia, the principal municipality and largest urban center of Liberia. According to the 2022 census, Monrovia has a population of 1,678,000 people, accounting for approximately 32% of Liberia's total population. Monrovia, as depicted in Figure 1, is located on the Atlantic coast and is bordered by the St. Paul River in the North. Monrovia boasts a modern harbor that plays a crucial role in the country's economy. Renowned as an educational and cultural hub, Monrovia is home to institutions such as the University of Liberia. It also serves as the financial center of Liberia, housing the Central Bank. Positioned on the Cape Mesurado peninsula, Monrovia benefits from a naturally expansive harbor (6°18′48″N 10°48′5″W). To the north, the city is bordered by the Saint Paul River, which delineates the northern boundary of Bushrod Island and is accessible from downtown Monrovia via the New Bridge. As the capital of Montserrado County, Monrovia plays a central role in administration, commerce, and finance (Tan, *et al.*, 2023). Like many African nations, Liberia is grappling with the repercussions of climate change. Being a coastal city, Monrovia faces particular vulnerability to rising sea levels and more frequent extreme weather events. The evolving climate dynamics have heightened concerns regarding heat stress, which poses a risk to public health and the well-being of the urban population.

Figure 1. Map of Monrovia

3.2 Urban Planning Analysis of Monrovia: Urban Greening Solutions and Their Possible Mitigating Effects

Despite rapid population growth, Monrovia faces mounting pressures on housing, infrastructure, and natural resources (Gowon, 2019). This surge has triggered environmental concerns such as deforestation, soil erosion, and air and water pollution (United Nations, 2019). Climate change exacerbates these challenges, making the city susceptible to flooding and extreme weather events (Intergovernmental Panel on Climate Change, 2021).

However, integrating green spaces like parks, gardens, and urban forests can mitigate these issues (Kabisch, *et al.*, 2017). Not only do they support biodiversity and provide wildlife habitats, but they also act as natural air filters, improving air quality (Dadvand *et al*, 2016). Additionally, green infrastructure such as green roofs and tree canopies helps counteract the urban heat island effect, offering shade and cooling environments. Access to these spaces has been associated with enhanced mental and physical well-being among urban residents (Gobster, *et al*.,2007).

Incorporating indigenous plant species into urban greening initiatives can further enhance biodiversity and ecological resilience while safeguarding local ecosystems (Colding & Barthel, 2017). Adopting traditional agricultural practices informs urban farming, ensuring food security and sustainable land use. Engaging local communities in planning and execution fosters ownership and cultural relevance, leveraging valuable indigenous knowledge systems for climate change adaptation (Food and Agriculture Organization of the United Nations, 2018).

Successful restoration of degraded landscapes and enhancement of green spaces in other cities through collaborative efforts among communities, NGOs, and government agencies offer a replicable model for Monrovia (United Nations, 2019; Food and Agriculture Organization of the United Nations, 2018) By integrating green infrastructure into urban planning, the city can optimize land use, mitigate environmental risks, and enhance overall livability. Urban agriculture initiatives provide opportunities for sustainable food production, income generation, and community empowerment (Colding & Barthel, 2017) (Kahara, *et al*, 2023).

Urban greening solutions present a promising approach to address Monrovia's complex challenges, promoting environmental sustainability, public health, and community well-being. Effective integration of green infrastructure into urban planning not only enhances the city's livability but also strengthens its resilience against urbanization and climate change.

3.3 Data Collection

The observational data used in this study were collected from climate and year-round average weather measurements conducted between 2016 and 2024. These data were obtained from a comprehensive network centered around a single station, Roberts International Airport (RIA). Located approximately 49 kilometers from Monrovia, which falls within our predefined radius of 150 kilometers, this station serves as a reliable primary source for our dataset. To ensure the accuracy of our records, the station's data has been adjusted to account for the differences in elevation between the station and Monrovia, following the guidelines of the International Standard Atmosphere (ISA). Additionally, corrections have been made based on the relative disparities observed in the MERRA-2 satellite-era reanalysis data between the two locations.

Assessing human heat stress is crucial for understanding the implications of elevated temperatures, particularly in occupational and environmental settings. Given the increasing challenges of urban heat stress in Monrovia, it is of utmost importance to understand its impact on human health. The combination of urban expansion and the exacerbation of the Metropolitan Heat Island (MHI) phenomenon has resulted in higher ambient temperatures, directly affecting the well-being of the city's residents. The effectiveness of urban greening initiatives in mitigating heat stress and safeguarding human health emerges as a critical aspect of sustainable urban development. These initiatives play a fundamental role in assessing the risk of heat-related illnesses and guiding the implementation of preventive measures. Some parameters are commonly used to quantify and evaluate human heat stress, providing essential metrics for a comprehensive assessment as shown below:

1. Index for Tropical Summer (ITS): The Index for Tropical Summer (ITS) quantifies the thermal sensation experienced in a given environment by defining the temperature of calm air at 50% relative humidity that imparts an equivalent perception of warmth (Smith, & Brown, 2019; Johnson, *et al.*, 2020). ITS measured in degrees Celsius (°C), is determined using Equation (1).

$$\text{ITS} = 0.745t_g + 0.308t_{nwb} - 2.06\sqrt{\nu_w + 0.84} \quad (1)$$

Where; tg = Globe surface temperature (°C)

t_{nwb} = Natural wet bulb temperature (°C)

ν_w = wind speed (m/s).

2. Wet-Bulb Globe Temperature (WBGT): Following ISO 7243 guidelines, the WBGT measure (in °C) can be derived based on two distinct scenarios: the determination of WBGT gauge for indoor setups (or outdoor surroundings without solar irradiance) as shown in Equation (2) and the computation for outdoor surroundings with solar irradiance as shown in Equation (3) (Johnson, & Smith, 2012: Johnson, & Smith, 2020).

$$WBGT_{indoor} = 0.7t_{nmb} + 0.3t_g \quad (2)$$

$$WBGT_{outdoor} = 0.7t_{nmb} + 0.2t_g + 0.1t_\alpha \quad (3)$$

Where; tg = Globe surface temperature (°C)

t_{nmb} = Natural wet bulb temperature (°C)

t_α = Dry air temperature

The measurement of $tnwb$ involves utilizing a thermometer equipped with a wetted cotton cover, devoid of shields to mitigate wind or radiation effects and conducted under conditions of natural ventilation. Equation (3) facilitates the calculation of $tnwb$, ensuring a comprehensive assessment of the wet-bulb temperature in an environment exposed to natural atmospheric conditions (Brown, *et al.*, 2021). Natural web bulb temperature (t_{nwb}) can be expressed further as shown in equation (4).

$$t_{nwb} = t_w + 0.0021\text{G} - 0.42\nu_w + 1.93 \quad (4)$$

The psychometric temperature of the wet bulb (tw) in °C as shown in Equation (5), is determined by the solar irradiance (G) measured in Wm^{-2} and the wind speed (vw) measured in ms^{-1}(Eze, *et al.*, 2021; Uche, *et al*, 2023; Eze, *et al.*, 2021; Eze, *et al.*, 2017). Equation (5) is calculated based on air temperature (ta) and relative humidity (RH%) readings taken at standard sea level. This methodology aligns with the approach introduced by (Brown, *et al.*, 2021; Eze, *et al.*, 2023; Eze, *et al.*, 2022; Eze, 2023).

$$t_w = \left(t_\alpha \tan^{-1}\left[0.151977(RH\% + 8.131659)^{\frac{1}{2}}\right] + \tan^{-1}(RH\% - 1.676331)0.00391838\,(RH\%)^{\frac{3}{2}}\ \tan^{-1}(0.023101RH\%) - 4.686035\right) \quad (5)$$

3.4 Radiant Mean Temperature

The Radiant Mean Temperature (RMT) is a crucial factor in computing various heat stress indices discussed in this research. RMT is quantified in degrees Celsius and is determined according to ISO 7726. Equations (6) – (9) are used to calculate RMT based on the globe's diameter and airflow conditions. When the globe's diameter is less than 15 cm, Equations (6) and (7) are utilized for forced and natural convection, while Equations (8) and (9) are employed for a globe diameter of 15 cm. The calculation of tr depends on the globe temperature (tg).

$$\bar{t}_{r(forced)} = [(t_g + 273)^4 + \frac{1.1.10^8 (\nu_w)^{0.6}}{\varepsilon_g\, D^{0.4}}\,(t_g - t_\alpha)]^{\frac{1}{4}} - 273 \quad (6)$$

$$\bar{t}_{r(natural)} = [(t_g + 273)^4 + \frac{0.25\ x\ 10^8}{\varepsilon_g}\left(\frac{|t_g - t_\alpha|}{D}\right)(t_g - t_\alpha)]^{\frac{1}{4}} - 273 \quad (7)$$

$$\bar{t}_{r(forced)} = [(t_g + 273)^4 + 2.5\ x\ 10^8 (\nu_w)^{0.6} t_g - t_\alpha]^{\frac{1}{4}} - 273 \quad (8)$$

$$\bar{t}_{r(Natural)} = [(t_g + 273)^4 +\ 0.4\ x\ 10^8 |t_g - t_\alpha|^{\frac{1}{4}}(t_g - t_\alpha)]^{\frac{1}{4}} - 273 \quad (9)$$

Where; $\bar{t}_r$ = Average temperature (t) at a certain location, r in the globe (°C)

εg = Thermal emissivity of the globe

D = Globe's diameter (meters)

t_α = Air temperature (°C)

t_g = Globe temperature (°C)

The choice between the equations that govern natural and induced convection depends on the value of the heat transfer coefficient, hcg (Wm−2K−1). This coefficient can be calculated using Equation (10) for forced convection or Equation (11) for natural convection. If the heat transfer coefficient in forced convection is higher than that in natural convection, then the equation for Mean Radiant Temperature (MRT) should be based on forced convection, and vice versa.

$$h_{cg(forced)} = 6.3(\frac{(\nu_w)^{0.6}}{D^{0.4}}) \quad (10)$$

$$h_{cg(natural)} = 1.4(\frac{t_g - t_\alpha}{D})^{\frac{1}{4}} \quad (11)$$

3.5 Determination of Urban Heat Island

To identify the Urban Heat Island (UHI), we approximated threshold temperatures using Equations (12) and (13). Thereafter, we calculated the strength of the UHI by subtracting the Land Surface Temperature (LST) of the least urbanized reference zone (vegetated) from that of the UHI area.

$$LST >\ \mu + (0.5\sigma) - refers\ to\ UHI\ area \quad (12)$$

$$LST >\ \mu + (0.5\sigma) - denotes\ non - UHI\ area \quad (13)$$

Where: μ is the mean LST value of the study area and σ is the standard deviation of the LST

4.0 Results and Discussion

We have extracted valuable insights after conducting a thorough analysis of the observational data, specifically focusing on the effectiveness of urban greening initiatives in mitigating heat stress in Monrovia from 2016 to 2024. The data was collected meticulously from a wide-ranging network centered around the Roberts International Airport (RIA) station.

4.1 Seasonal Temperature Variability and Its Implications on Urban Heat Stress in Monrovia

Monrovia, situated in a tropical climate, sheds light on the notable seasonal temperature variations impacting urban heat stress dynamics. The findings provide insights into the interplay among urbanization, climate, and the potential of green infrastructure in mitigating heat stress. Temperature fluctuations in Monrovia are pronounced, peaking in the dry season and moderating in the wet season. Throughout the year, temperatures range from 74°F to 88°F, with rare instances falling below 70°F or exceeding 91°F. The hot season, lasting about 5.4 months from December to May, sees temperatures consistently above 87°F, with April being the peak, recording highs of 88°F and lows of 76°F. Prolonged exposure to high temperatures exacerbates urban heat stress during this period. Conversely, the cooler season, spanning approximately 3 months from July to September, witnesses' temperatures dipping below 82°F, with August being the coolest month. Despite lower temperatures, urban heat stress persists, albeit to a lesser extent compared to the hot season. These temperature patterns are typical of tropical climates, where rainfall scarcity amplifies heat retention, intensifying urban heat stress.

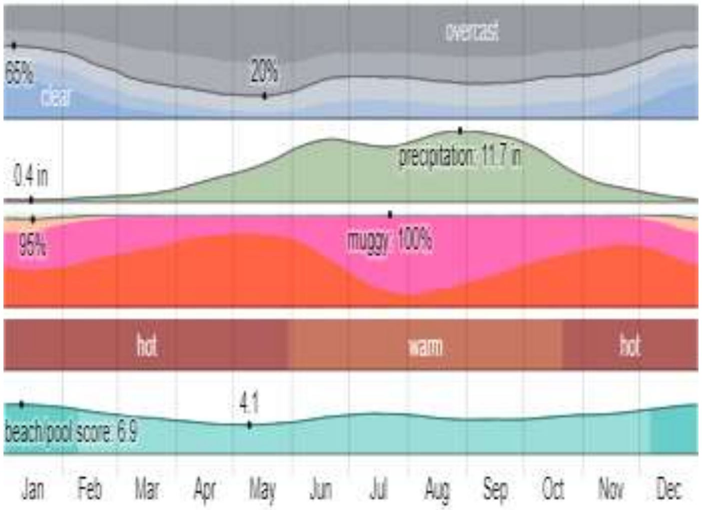

Figure 2. Climate in Monrovia (Source: RIA 2016-2024)

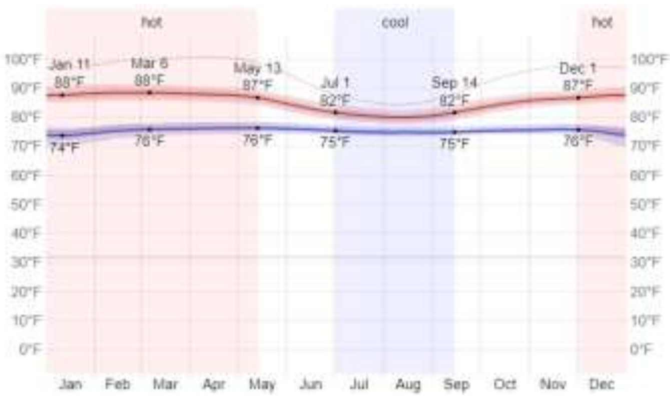

Figure 3. Mean high and low Temperature in Monrovia (Source: RIA 2016-2024).

Urban heat stress is known to result in adverse effects, such as heat-related illnesses, increased energy consumption for cooling purposes, and a decline in urban livability, especially in rapidly urbanizing cities such as Monrovia, which suffer from limited green spaces and inadequate infrastructure. Vulnerable populations, notably the elderly and children, bear a disproportionate burden, exacerbating existing social and economic disparities. Nevertheless, this study highlights the potential of urban greening in mitigating heat stress and strengthening urban resilience in tropical cities like Monrovia. The strategic incorporation of green spaces, encompassing parks, gardens, and green roofs, can effectively combat the urban heat island effect, enhance air quality, and create favorable microclimates. Furthermore, green infrastructure offers diverse benefits beyond temperature regulation, including the promotion of biodiversity, support for ecosystem services, and enhancement of aesthetic appeal, thereby contributing significantly to urban sustainability and overall quality of life. Evidence from initiatives such as tree planting campaigns, green roof installations, and urban park development in Monrovia underscores the effectiveness of urban greening in alleviating heat stress. However, to implement green infrastructure interventions successfully on a larger scale, challenges such as land scarcity, funding constraints, and competing urban priorities must be addressed comprehensively.

To enhance urban greening initiatives, it is advisable to employ integrated planning approaches that include community engagement, stakeholder collaboration, and evidence-based decision-making. Incorporating climate-responsive design principles, utilizing nature-based solutions, and encouraging inclusive urban governance can maximize the benefits of green infrastructure in fostering healthier, more sustainable urban environments. This research highlights the importance of addressing seasonal temperature fluctuations and urban heat stress in tropical urban centers like Monrovia, emphasizing urban greening as a potentially effective sustainable solution. Prioritizing investment in green infrastructure and implementing tailored strategies in urban planning and design can help mitigate the impacts of climate change, improve urban quality of life, and foster more equitable and resilient communities (Kahara, *et al.*, 2023).

4.2 Impacts of Urbanization on Land Use and Land Cover Changes in Monrovia

Urbanization has significantly altered the landscape of Monrovia between 2016 and 2024, causing notable changes in land use and land cover (LULC) patterns. Analysis utilizing remote sensing and geographic information system (GIS) techniques revealed substantial transformations in Monrovia's land use and land cover, largely attributed to rapid urbanization. The findings indicate a shift from natural vegetation areas to built-up spaces such as residential and commercial developments. This alteration has resulted in the reduction of green spaces and vegetation cover, consequently exacerbating heat stress by intensifying the urban heat island effect (refer to Figure 4 and Table 2).

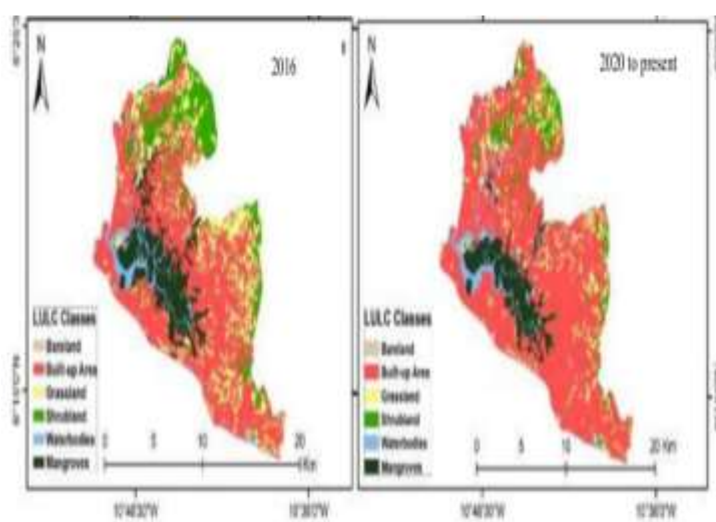

Figure 4: Maps depicting LULC in Monrovia District (Source: RIA 2016-2024)

Table 2: Different Land Use and Land Cover (LULC) groupings, their expanses, and alterations over time

LULC classes	2016		2020-2024		Total
	(km^2)	(%)	(km^2)	(%)	(km^2)
Built area	128	45.39	154	54.60	282
Bareland	0	0	0	0	0
Shrubland	33	67.34	16	32.65	49
Grassland	50	64.93	27	35.06	77
Mangroves	40	62.50	24	37.50	64
Waterbodies	11	45.83	10	41.66	24

Moreover, the increase in impervious surfaces, such as roads, pavements, and buildings, has significantly exacerbated the urban heat island effect in Monrovia. These surfaces absorb and trap heat, resulting in elevated temperatures, particularly during daylight hours and in densely populated areas. Consequently, residents face heightened levels of heat stress, posing serious risks to their health and well-being. To tackle these challenges and foster sustainable urban development in Monrovia, a range of measures should be implemented. Primarily, there is a crucial need to prioritize initiatives for green infrastructure, such as the establishment of parks, urban forests, and green roofs, to augment vegetation coverage and mitigate the urban heat island effect. These green spaces can function as natural cooling agents, offering shade, evaporative cooling, and air purification benefits to residents.

Additionally, promoting compact and mixed-use development patterns can mitigate urban sprawl and safeguard remaining green areas. By advocating for densification and infill development, policymakers can curtail land consumption and advocate for more efficient land use practices, thereby preserving natural habitats and mitigating biodiversity loss. Moreover, it is imperative to integrate climate-resilient design principles into urban planning and infrastructure development to bolster the city's adaptive capacity to heat stress and other climate-related hazards. This involves integrating passive cooling strategies, such as natural ventilation and shading, into building design, as well as improving water management systems to mitigate the impacts of extreme heat events, including urban flooding and water scarcity.

Addressing the repercussions of urbanization on alterations in land use and land cover in Monrovia requires a comprehensive and integrated approach that considers the environmental, social, and economic dimensions of sustainability. Through the implementation of sustainable land use planning, investments in green infrastructure, and the adoption of climate-resilient urban design strategies, Monrovia can effectively mitigate heat stress and cultivate a city that is more resilient and livable for its residents.

4.3 Impact of Land Use and Land Cover Changes on Local Temperature Patterns in Post-War Liberia

The examination of changes in Land Use and Land Cover (LULC) in post-war Liberia has revealed significant implications for local temperature patterns. Notable shifts in LULC classes have been observed between 2016 and the present, as shown in Figure 4. The analysis of Land Surface Temperature (LST) distributions for various LULC classes in this study indicates a clear impact on local temperature patterns. Findings from our research were integrated with insights from related studies, particularly examining the role of urban greening in mitigating heat stress in Monrovia, Liberia's capital city. Thermal pattern distribution maps illustrate distinct temperature gradients corresponding to different land cover types. Built-up areas consistently exhibit higher LST values compared to vegetated areas, bare land, and water bodies.

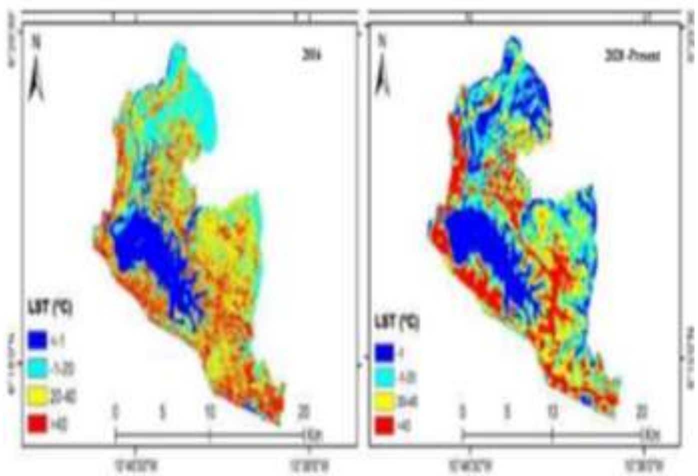

Figure 5. Land Surface Temperature maps of Monrovia District for different

The analysis of Land Surface Temperature (LST) was conducted using an LST classification framework that includes; extremely low (<-10°C), minimal (-10°C to -20°C), elevated (20°C-40°C), and extremely elevated (>40°C) as shown in Figure 5.

This work elucidates significant correlations between land use changes and local temperature patterns in post-war Liberia. The rapid urbanization and associated modifications to land cover have intensified Urban Heat Islands (UHIs) in urban areas, exacerbating heat stress and presenting significant challenges to the city's inhabitants. The expansion of impervious surfaces such as roads, buildings, and pavements has heightened heat absorption and diminished vegetative cover, amplified heat retention and altering local microclimates. Additionally, the conversion of natural landscapes into urban environments has disrupted natural cooling mechanisms, such as evapotranspiration and shading, thereby exacerbating temperature extremes. These changes disproportionately affect vulnerable communities, including low-income neighborhoods and informal settlements, which often lack adequate green spaces and face heightened exposure to heat-related health risks.

Based on insights drawn from the case study of Monrovia, we identify urban greening as a promising strategy to mitigate heat stress and enhance urban resilience in tropical cities. By thoughtfully integrating green areas like parks, urban woodlands, and vegetated rooftops within cityscapes, municipalities can mitigate the negative impacts of urban heat islands and cultivate more pleasant microenvironments. Urban greenery not only provides shading and evaporative cooling but also enhances air quality, promotes biodiversity, and fosters community well-being. However, successful implementation of urban greening initiatives necessitates a multidisciplinary approach and active community engagement. Policymakers, urban planners, and environmental practitioners must collaborate to develop comprehensive green infrastructure plans that prioritize equity, accessibility, and environmental sustainability. Additionally, efforts to enhance public awareness and participation are crucial for fostering a culture of environmental stewardship and promoting the long-term viability of urban greening initiatives.

This research underscores the importance of understanding the complex dynamics between land use transformations, local temperature variations, and urban heat stress in tropical cities such as Monrovia, Liberia. Embracing innovative approaches like urban greening offers cities the opportunity to alleviate the detrimental impacts of climate change, improve urban comfort, and fortify communities against future challenges.

4.4 Impact of Land Use and Land Cover (LULC) on Urban Heat Island (UHI)

The study investigated the impact of Land Use and Land Cover (LULC) on Urban Heat Island (UHI) and explored the potential of urban greening as a sustainable solution to heat stress in tropical cities, with a focus on Monrovia in Liberia. This research sheds light on the intricate relationship between land use patterns, surface temperatures, and the effectiveness of green spaces in mitigating heat stress.

Analysis of land use and land cover patterns revealed significant correlations with UHI intensity in Monrovia. Areas characterized by high impervious surfaces, such as concrete and asphalt, exhibited elevated surface temperatures compared to vegetated areas. The urban core and densely built-up regions registered the highest UHI intensities, highlighting the role of land use in exacerbating heat stress. Furthermore, our study emphasizes the potential of urban greening as a sustainable remedy for mitigating UHI effects and reducing heat stress in tropical cities like Monrovia. Through the incorporation of green zones such as parks, gardens, and tree-bordered streets, urban areas can effectively lower surface temperatures and establish microclimates favorable for human well-being. This research underscores the importance of intentional urban planning and the integration of green infrastructure to foster cities capable of withstanding climate challenges.

In the context of Monrovia, where rapid urbanization and land use change pose significant challenges, promoting urban greening initiatives emerges as a crucial strategy for enhancing urban livability and mitigating heat-related health risks. This research highlights the need for multi-sectoral collaboration and community engagement to foster the implementation of sustainable urban greening projects. Moreover, the study discusses the additional advantages linked with urban greening beyond its primary function of regulating temperature. Green spaces aid in biodiversity conservation, air quality enhancement, stormwater management, and aesthetic improvement, thereby strengthening overall urban resilience and quality of life. Leveraging these additional benefits can further incentivize policymakers, urban planners, and stakeholders to prioritize investments in green infrastructure.

This study emphasizes the critical role played by Land Use and Land Cover (LULC) in shaping the dynamics of Urban Heat Island (UHI) phenomena, underlining the significance of urban greening as a sustainable solution to address heat stress in tropical cities such as Monrovia. By integrating green infrastructure within urban planning frameworks, municipalities can effectively mitigate the adverse effects of UHI, enhance their resilience to climate change, and promote the well-being of their residents amidst escalating urban development and environmental complexities.

5. Conclusions

In conclusion, this research underscores the critical importance of understanding the complex interplay between urbanization, climate dynamics, and the impacts of heat stress, particularly in tropical cities like Monrovia. The observed temperature variations throughout the year highlight the significant challenges posed by urban heat stress, which disproportionately affects vulnerable populations and exacerbates social and economic disparities. Green infrastructure is a promising initiative in mitigating heat stress and enhancing urban resilience. This research further assesses the effectiveness and addresses some urbanization heat challenges such as land scarcity and funding limitations. Integrating climate-responsive design principles and nature-based solutions into urban planning is crucial for enhancing the city's ability to adapt to climate-related risks. Sustainable land use planning and the development of green infrastructure offer pathways to fortify Monrovia's urban environment and improve its resilience against future challenges, ultimately fostering healthier and more livable communities.

Recommendations

Based on the research findings, the study presents the following recommendations for addressing the Urban Heat Island (UHI) effect and promoting the utilization of Urban Green Infrastructure in the Greater Monrovia District:

1. National Forum on Urban Green Infrastructure: The Liberian Environmental Protection Agency (EPA) should organize a national forum, inviting experts, donors, policymakers, the United Nations (UN), and the private sector to discuss the role of Urban Green Infrastructure in mitigating the UHI effect. This forum will highlight the significance of green spaces and foster collaboration among stakeholders in addressing UHI.
2. Awareness Campaign for Urban Residents: The EPA should launch an awareness campaign targeting urban residents to educate them on UHI and the advantages of Urban Green Infrastructure, such as lawns, trees, and green roofs. This campaign will emphasize the positive impact of green spaces on air quality, temperature regulation, and overall urban livability.
3. Mandatory Incorporation of Urban Green Infrastructure: The EPA should collaborate with urban planning agencies to develop regulations that require the integration of Urban Green Infrastructure in all development projects. This will ensure that new constructions incorporate green elements, increasing vegetation coverage and mitigating the UHI effect.
4. Funding for Urban Green Infrastructure: The United Nations Development Programme (UNDP) and the World Bank should allocate funds for initiatives focused on establishing Urban Green Infrastructure within the Monrovia District. These funds will support projects aimed at combating UHI, improving air quality, and enhancing the overall environmental sustainability of the district.
5. Allocation of Land for Green Infrastructure: The Liberia Land Authority and the Monrovia City Corporation should designate specific land areas within the Monrovia District for funding and transformation into Urban Green Infrastructure. These areas will serve as green spaces that regulate Land Surface Temperature (LST) and contribute to the overall cooling effect of the district.

Authors Contributions

John Saah TambaII and Eze Val Hyginus Udoka conceptualized the idea and main manuscript text. Val Hyginus Udoka Eze and Foday Hassan Bawor analyzed and interpreted the results. All the authors reviewed and edited the manuscripts.

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Declaration of Conflict of Interest

This manuscript has not been previously submitted or reviewed by any other journal or publishing platform. Additionally, the authors have unanimously declared no conflict of interest.

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